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Co-Firing of Solid Wastes and Coal at Ames: Stoker Boilers

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16. ABSTRACT

This report presents an evaluation of the Ames Solid Waste Recovery System through the second full year of its operation (1977). This evaluation includes the operating experience and economics of the refuse processing plant, the characterization of the various material flow streams within the refuse processing plant, and the thermodynamic and mechanical performance and the environmental emissions of the stoker-fired steam generators.

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September 1985

CO-FIRING OF SOLID WASTES AND COAL AT AMES: STOKER BOILERS

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

On August 30, 1975, the first continuous, full-scale solid waste recovery system for the processing and burning of municipal solid waste as a supplementary fuel for power generation commenced operation in the City of Ames, Iowa. This report provides the cumulative results of the Ames, Iowa, refuse processing plant experience during its second full year of operation (1977). It provides basic data on the economics of operating the plant, the operating experience, the characterization of refuse-derived fuel, and the performance and environmental emissions results from the study of the performance of the stoker-fired steam generators at the City of Ames.

The information contained herein will be of interest to those designers or users who are contemplating or working with a system similar to the Ames system. Requests for further information regarding the production and utilization of refuse-derived fuel should be directed to the Thermal Destruction Branch, HWERL, Cincinnati.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

This research program is titled "Evaluation of Ames Solid Waste Resources and Energy Recovery System," with the objectives being to conduct an in-depth evaluation of the environmental, economic, and technical aspects of the resource and energy recovery system located in Ames, Iowa. The recovery system includes recovery of ferrous and aluminum metals, preparation of the refuse-derived fuel (RDF), storage for the RDF, and co-firing the RDF with coal in the City of Ames-owned power plant to produce electric power.

The evaluation period for the research program covered 3 years of research. This report, which evaluates the second year of research, includes evaluations of the refuse processing plant operation, economics of the total system and individual subsystems, flow stream characterization, performance of the stoker-fired steam generators, and environmental emissions of the stoker-fired steam generators. Where data are available for both the first and second year of research, comparisons of the two are made. Data acquired during the first year's research were previously reported in three Environmental Protection Agency Reports; No. EPA-600/2-77-205, "Evaluation of the Ames Solid Waste Recovery System, Part I - Summary of Environmental Emissions: Equipment, Facilities, and Economic Evaluations," EPA-600/7-79-229, "Evaluation of the Ames Solid Waste Recovery System, Part II - Performance of the Stoker Fired Steam Generators," and EPA-600/7-79-222, "Part III - Environmental Emissions of the Stoker Fired Steam Generators."

This report was submitted in partial fulfillment of Grant No. R803903-01-0 by the City of Ames under the sponsorship of the U.S. Environmental Protection Agency. Research studies were conducted by Engineering Research Institute of Iowa State University and Midwest Research Institute in cooperation with the Ames Laboratory, Department of Energy. This report covers the period from February 1977 through January 1978.

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SECTION 1

INTRODUCTION

The Ames Solid Waste Recovery System is a continuously operating system that is processing municipal solid waste (MSW) for use as a supplemental fuel in the existing steam generators of the Ames Municipal Power Plant. The total system consists of a nominal 136-Mg/day (150-ton/day) processing plant, a 454-Mg (500-ton) Atlas storage bin, pneumatic transport systems, and the existing municipal power plant. The processing plant incorporates two stages of shredding, ferrous and nonferrous metal recovery, and an air density separator. The three steam generators consist of one pulverized coal tangentially fired unit (No. 7) and two stoker-fired return traveling grate spreader units (Nos. 5 and 6).

The first MSW was fed through the plant on August 30, 1975. This was followed by a 4-month start-up period; the plant was considered fully operational for evaluation purposes by January 1, 1976. The Environmental Protection Agency (EPA) Grant No. R803903-01-0 for the research study of the Ames Solid Waste Recovery System was officially awarded February 4, 1976. The Department of Energy (DOE) contract supporting this work is W-7405 Eng 82.

This report is concerned with the following objectives:

- Evaluation of the refuse processing plant performance
- Economic evaluation of the Ames Resource Recovery System
- Characterization of the material flow streams within the refuse processing plant and the refuse-derived fuel produced
- Evaluation of the performance of the stoker-fired boilers
- Measurement of environmental emissions from the stoker-fired boilers
- Determination of boiler tube corrosion in the stoker-fired boilers.

This report will present the results and conclusions of the tests performed through the second year of evaluations (1977). The report contains separate sections on each of the above six listed objectives.

Previous evaluations conducted through only the first year (1976) are contained in the following three reports:

- "Evaluation of the Ames Solid Waste Recovery System: Part I - Summary of Environmental Emissions, Equipment, Facilities and Economic Evaluations." EPA-600/2-77-205, U.S. Environmental Protection Agency.
- "Evaluation of the Ames Solid Waste Recovery System: Part II - Performance of the Stoker-Fired Steam Generators." EPA-600/7-79-229, U.S. Environmental Protection Agency.
- "Evaluation of the Ames Solid Waste Recovery System: Part III - Environmental Emissions of the Stoker-Fired Steam Generators." EPA-600/7-79-222, U.S. Environmental Protection Agency.

SECTION 2

REFUSE PROCESSING PLANT ACTIVITY

This section addresses the operating experience of the general plant and the following subsystems:

- Tipping Floor
- Shredder System
- Air Density Separator System (ADS)
- Rejects
- Ferrous Metal Separation System
- Aluminum Separation System
- Pneumatic Conveying System (PSI)
- Atlas Bin

A description of the refuse processing system is presented first and is followed by a discussion of the operating experience.

PLANT DESCRIPTION

Figure 1 is a block flow diagram of the processing plant. MSW is delivered to the tipping floor which is 48 m by 32 m and has two entrances and exits. One is for commercial trucks and the other for private automobiles and pickup trucks. The commercial trucks are weighed on a truck scale, and the private vehicles are simply counted. A front-end loader is used to push the MSW onto the infeed conveyor C-1.

Raw refuse first enters the plant processing system via infeed conveyor C-1 into the first stage shredder, then via conveyor C-3 through the second stage shredder. A magnetic belt separator removes ferrous metal from the material flow stream between the first and second stage shredder. Conveyor C-6 transports the material from the second stage shredder into the air density

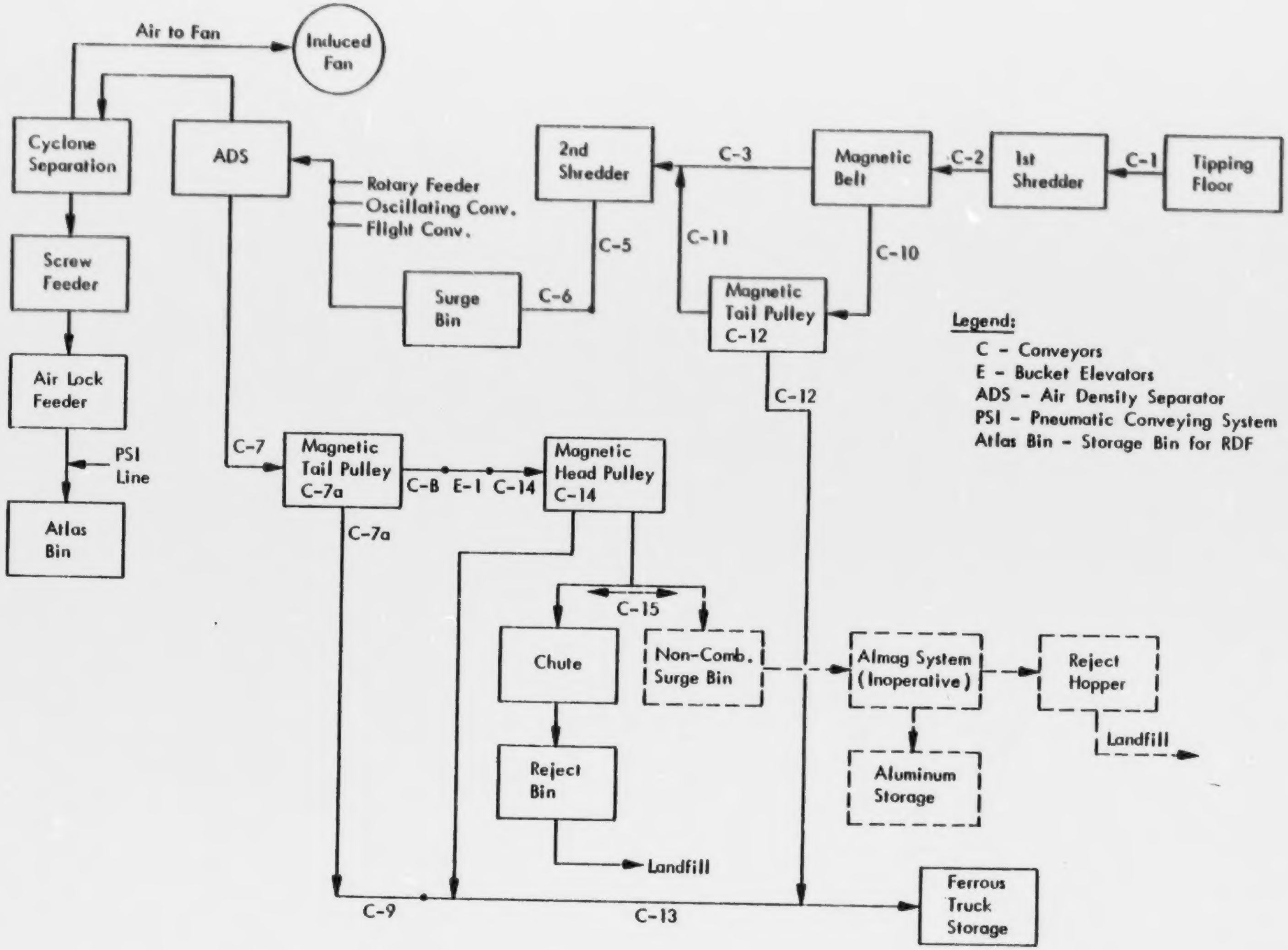

Air to Fan
Induced Fan
Cyclone Separation
ADS
Rotary Feeder
Oscillating Conv.
Flight Conv.
2nd Shredder
C-3
Magnetic Belt
C-2
1st Shredder
C-1
Tipping Floor
C-5
C-11
C-10
Screw Feeder
Surge Bin
C-6
Magnetic Tail Pulley C-12
Legend:
C - Conveyors
E - Bucket Elevators
ADS - Air Density Separator
PSI - Pneumatic Conveying System
Atlas Bin - Storage Bin for RDF
Air Lock Feeder
C-12
PSI Line
C-7
Magnetic Tail Pulley C-7a
C-B
E-1
C-14
Magnetic Head Pulley C-14
Atlas Bin
C-7a
C-15
Chute
Non-Comb. Surge Bin
Almag System (Inoperative)
Reject Hopper
Landfill
Aluminum Storage
Reject Bin
Landfill
Ferrous Truck Storage
C-9
C-13

Figure 1. Flow diagram of Ames Solid Waste Processing Plant.

separation (ADS) subsystem. Light material is transported via a pneumatic conveying system (PSI) to a storage bin (Atlas bin) prior to transport to the electric power generating plant. The heavy material drops out of the ADS onto conveying belts where it is transported to a reject bin. Material in the reject bin is periodically transported by truck to a landfill. Additional ferrous metal recovery is achieved from the ADS heavy material by a magnetic tail pulley and a magnetic head pulley. This ferrous metal is added to the ferrous metal recovered by the magnetic belt separator.

An aluminum separation system (Almag) composed of a trommel screen and an electrical eddy current separator was originally installed at the plant, but this system is now inoperative. It is shown in dotted lines on Figure 2.

GENERAL PLANT OPERATING EXPERIENCE

Operation of the process plant during 1977 represented the second year of operation. Processing occurred on a 5 day/week basis. On Saturday, no processing was scheduled, but a two-person crew received refuse from private citizens. The plant operated 234 days out of a possible maximum (allowing for holidays) of 254 days during 1977 for a percentage availability of 92%.

The major occurrences which caused downtime in excess of 1 day were:

- Ruptured water line
- Pneumatic pipeline repairs/replacement
- Repair of the Atlas bin floor
- Fire in the Atlas bin
- Shredder fires and other bin fires

Ruptured Water Lines

On Sunday, January 2, 1977, a water line in the basement ruptured from freezing causing the plant to be flooded. This pipe was not insulated, and the outside temperature reached -30°C during the 3-day holiday weekend. It is estimated that 1,000 m^3 of water filled the basement area. A downtime of 3 days resulted from the need to dry and repair electric motors. Plant operations resumed on January 6. During this time, the raw refuse received was diverted as landfill.

Pneumatic Pipeline Repairs/Replacement

On June 3 through 8, 1977, the 14-in. section of transport line between the process plant and Atlas bin was replaced. The first 91.5 m (300 ft) between the plant and access vault was removed, which resulted in 26 hr of nonprocessing, or downtime, plus weekend repair work.

On Monday, December 12, the pneumatic transport line to the Atlas bin was shut down for partial pipe replacement after the pipe had repeatedly plugged the previous Friday and then again on Monday. Approximately 61 m (200 ft) of line between the access vault and Atlas bin were replaced. Repairs were completed on December 14, but the pipe plugged again on December 15, which resulted in another day of downtime.

Atlas Bin Floor Repair

The process plant did not operate from Monday, June 20, 1977, until 2:00 p.m. Tuesday, June 28 (6 days) due to completion of floor repairs and resurfacing in the Atlas bin.

Extensive wear of the concrete floor had occurred since original system start-up exposing the concrete reinforcing rod. In addition, angle iron strips forming the edge between the concrete floor and the drag conveyor trench were worn and ripped away. New angle iron edging and 3.81 cm (1-1/2 in.) grizzly bars over the troughs were installed. The floor was resurfaced with a Meta-Crito LV epoxy - Wisconsin Trap rock aggregate (4 parts rock to 1 part epoxy). The use of only two of four drag infeed conveyor systems to supply RDF to the power plant resulted in high bin pull-ring rpm's and bucket travel speeds in order to satisfy the demand set-point RDF flow rate.

Atlas Bin Fire

About 5:30 p.m. on July 13, 1977, a fire was detected in the Atlas bin causing the process plant to be shut down during July 14 and 15. After completion of major fire fighting efforts by the Ames Fire Department, one power plant maintenance man and one fireman remained on duty to hose down any flare-ups that might occur. (The Atlas bin had to be emptied after the fire before any RDF could be added.) As the buckets pulled away material, smoldering RDF would flare up and start burning. All the RDF which was emptied from the bin was pneumatically transported to the power plant for boiler consumption. Total plant downtime from this fire was 16 hr.

Another bin fire occurred during the night of Thursday, November 17, resulting in no RDF processing Friday, November 18. Again the bin had to be emptied before new RDF input was allowed. Total downtime from this fire was 8 hr.

Shredder Fires and Other Bin Fires (Summary)

The number of shredder fires occurring in 1977 and their severity in terms of downtime were as follows:

Date	Location	Downtime (hr)
January 13	Shredder 1	1.17
February 23	Shredder 1	0.42
May 18	Not specified	1.0
July 22	Not specified	0.5
August 11	Shredder 1	0.92
	Shredder 2	0.92
	Shredder 2	0.17
August 31	Shredder 1	0.17
October 11	Shredder 1	0.67
November 17	Shredder 2	1.0
November 22	Shredder 1	0.92

Assuming that the unspecified plant fires were shredder fires, there were 11 shredder fires in 1977 and two storage bin fires. The shredder fires were of relatively minor consequence but emphasized the need for constant vigil and good extinguishing of or near the shredders.

SUBSYSTEM OPERATING EXPERIENCE

Tipping Floor

Figure 2 is a layout of the tipping floor showing its size relative to the production area, the storage area for raw refuse received, and the traffic patterns of the private car line, the scaled vehicles, and the front-end loader.

The tipping floor is adequate for normal operations; however, when refuse has accumulated for a period of 2 days during an extended period of downtime, the front-end loader is difficult to operate in the limited space remaining to load refuse onto the infeed conveyor C-1. The limit on raw refuse accumulation on the tipping floor is 3 days, and any additional refuse received has to be diverted to the landfill. The operation of the front-end loader is extremely difficult with a 3-day accumulation of raw refuse which reduces the processing rate.

Tipping floor operations proceeded smoothly during 1977. The only downtime attributed to the tipping floor was for repairs on the end loader during processing time. The three repair incidents accounted for a total 1.59 hr of downtime. The primary mechanical problem was the breakage of hydraulic lines

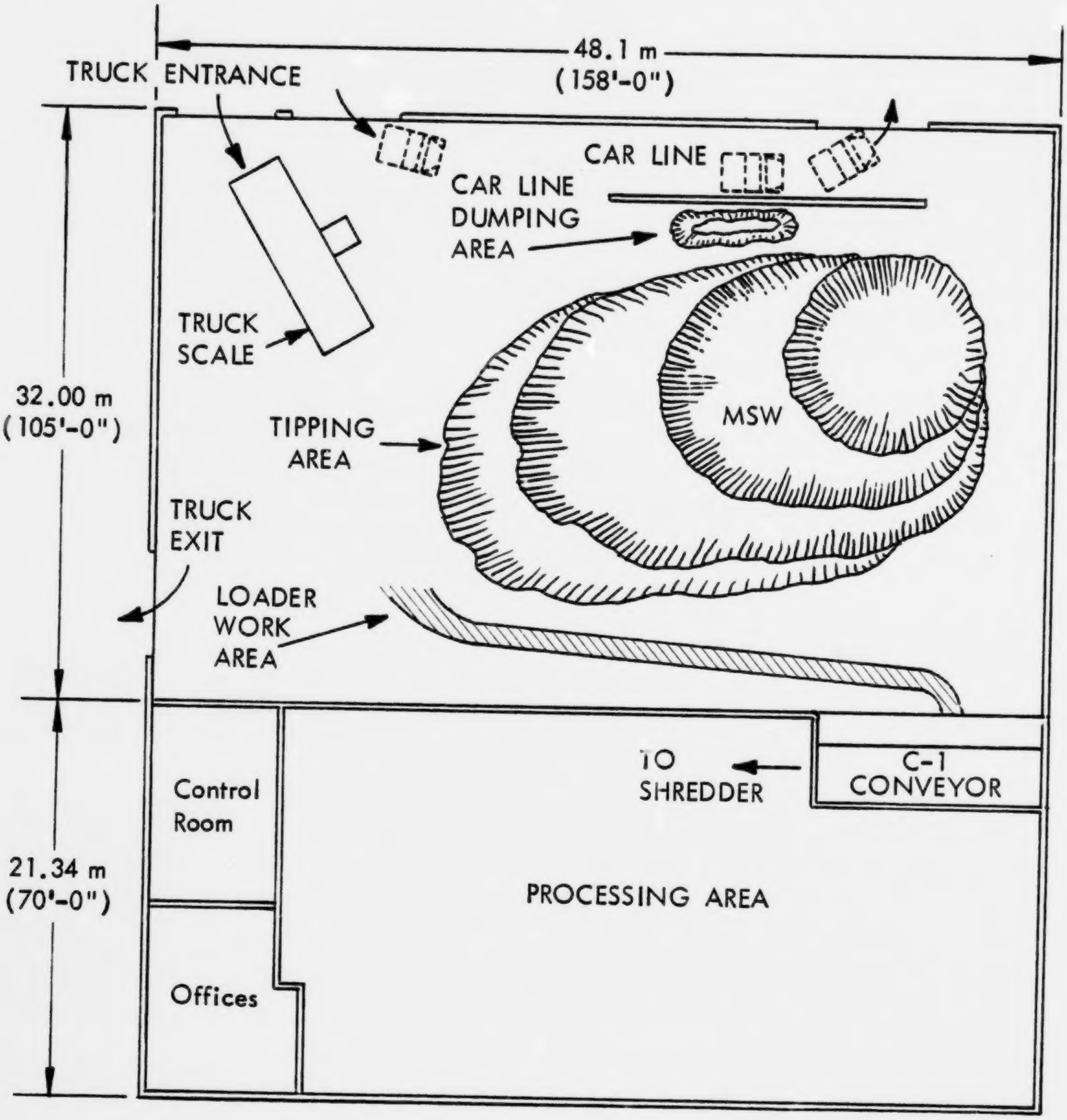

48.1 m
(158'-0")
TRUCK ENTRANCE
CAR LINE
CAR LINE
DUMPING
AREA
TRUCK
SCALE
32.00 m
(105'-0")
TIPPING
AREA
MSW
TRUCK
EXIT
LOADER
WORK
AREA
TO
SHREDDER
C-1
CONVEYOR
Control
Room
21.34 m
(70'-0")
PROCESSING AREA
Offices

Figure 2. Tipping floor layout.

and line couplers. The largest period of downtime was 0.92 hr. The shortest was 0.25 hr. Tipping floor operations were not as affected by mechanical failures as by the crowded conditions resulting from large accumulations of refuse. This typically occurred when other plant subsystems were also experiencing downtime.

Shredder System

The shredder system is composed of the primary and secondary shredders plus conveyors: the infeed conveyor to the primary shredder (C-1); the vibrating pan conveyor under the primary shredder (C-2); the infeed conveyor to the secondary shredder (C-3); the vibrating pan conveyor under the secondary shredder (C-5); and the conveyor which carries the twice-shredded refuse to the preceding air classification (C-6). This system performed reliably during 1977. Most downtime attributable to the shredder system resulted from broken and jammed flights on C-1, from the clogging of refuse in the C-3 hopper entering the secondary shredder, from the jamming of the C-3 belt at both the head pulley and tail pulley, or from wear on and overloading of the motor. Shredder fires, which have been previously discussed, also accounted for a small amount of downtime. Data on downtime for this system are summarized for the year in Table 1.

Hammer changes occurred on a nominal basis of once every 11,843 Mg (13,055tons) for the primary shredder and 7,315 Mg (8,063 tons) for the secondary shredder. Hammer changes are integrated into the plant maintenance schedule at the discretion of the plant manager. For the primary shredder, the average number of processing days between hammer changes was 54.5 (ranging from 42 to 73). The corresponding range of processed mass is 8,304 to 15,116 Mg. For the secondary shredder, the average number of processing days between hammer changes was 38.5 (ranging from 30 to 79). The corresponding range of processed mass is 4,986 to 15,810 Mg. Hammer change dates for the primary and secondary shredders were as follows for 1977:

Primary Shredder	Secondary Shredder
January 12	February 25
April 12	April 7
June 24	August 18
October 12	October 12
	December 20

Air Density Classification System

The air density classification system, commonly known as the ADS system, performed significantly better in 1977 than in 1976. This is believed to have been the result of an improved understanding of its operating characteristics and improved skill in adjusting airflow to meet changing

TABLE 1. SHREDDERS AND SHREDDER CONVEYORS DOWNTIME (1977)
(HR)

	Primary			Secondary		
	External	Internal		Internal		External
Date	C-1 Infeed	C-3 Hopper and motor	Fire (1)	Fire (2)	Misc.	C-5 Discharge
1/77	1.51	0.08	1.00	-	-	-
2/77	0.84	1.34	0.42	-	0.33	0.17
3/77	1.48	0.93	-	-	-	-
4/77	6.42	1.91	-	-	-	-
5/77	2.20	-	-	-	-	-
6/77	2.43	-	-	-	-	0.42
7/77	5.87	1.87	0.50	0.25	-	1.50
8/77	1.73	2.94	1.09	1.09	0.67	0.17
9/77	4.13	0.08	-	-	1.33	7.15
10/77	7.82	0.39	0.67	-	1.25	0.33
11/77	12.75	0.41	1.67	1.00	-	1.78
12/77	9.66	0.16	1.00	-	2.50	1.33
	56.84	10.11	6.35	2.34	6.08	12.85

conditions in infeed material during operations. Table 2, however, shows an increase in downtime in several of the ADS system components. The ADS system comprises a number of mechanical and pneumatic elements including the flight conveyor, scalping roll, vibrating screen, ADS rotary air lock feeder, cyclone, return air feed, heavy fraction conveyor (C-7), and others.

As shown in the table, most of the ADS downtime was attributed to the vibrating screen, the ADS rotary air lock feeder, the ADS reverse flow trap metalscreen filter (C-99), and heavy fraction conveyor (C-7). Of these, C-99 was by far the largest contributor. The cause of the problem with C-99 was excessive wear in the casing of the rotary air-lock feeder resulting in air leakage from the pneumatic line which backed up through the screw feeder and into the cyclone separator. This, in turn, produced an upset in the vortex separation of RDF from the ADS, which resulted in a conveyor of material with the air flowing back to the ADS fan through the reverse air trap filter (C-99). This conveyor of material accumulated on the filter causing plugging and subsequently downtime to clean the filter. Most of the rest of the increase in downtime was due to wear and fatigue caused by handling a dirty abrasive product in a dusty environment over a significant period of time.

Rejects

Material classified as rejects includes all the heavy fractions from the ADS except for the ferrous metal. Some of this material (wood, plastic, rubber) is combustible, and some (glass, grit, nonferrous metal) is not. The part of the flow stream following the drop-out of the ADS heavies is shown in Figure 4 and is described in the following discussion.

The small amount of ferrous metal present in the C-7 stream is removed by the C-7A magnetic tail pulley positioned above C-7. It is then transferred to conveyor C-9 and then to C-13 where it joins the previously separated ferrous material and is conveyed to the ferrous storage trailer.

After passing under the ferrous magnetic tail pulley on C-7A, the C-7 reject flow stream empties onto C-8 where it is discharged into the E-1 bucket elevator. The E-1 elevator discharges onto C-14, which also contains a magnetic tail pulley. The C-14 conveyor can be positioned to discharge the rejects onto C-15 and then to the reject hopper for landfilling or into the surge bin for entry into the nonferrous separator system. The nonferrous system was inoperative in 1977. The E-1 elevator experienced plugging both at the inlet chute and the discharge onto C-14, but plant operating time was not significantly affected. The inlet chute or hopper to E-1 from C-8 was enlarged, and this corrected the plugging problems.

TABLE 2. AIR DENSITY SEPARATOR SYSTEM DOWNTIME PER COMPONENT (JUNE 1976-DECEMBER 1977) (HR)

Date	Flight conveyor	Scalping roll (surge-bin)	Channel-5 C-7	Vibrating screen (ADS-link) belt	ADS feeder	ADS cyclone	Screw feeder	C-99 (ADS RET-air)	Heavies conveyor C-7	ADS misc.
6/76	0.42	-	-	-	0.42	-	3.00	1.00	0.91	-
7/76	-	-	0.50	0.25	1.51	-	-	0.55	0.46	0.50
8/76	0.17	0.03	-	-	0.50	-	-	-	0.25	0.76
9/76	-	0.34	-	-	1.16	-	-	0.80	1.10	0.17
10/76	-	0.17	0.50	-	0.17	0.17	0.67	1.08	2.42	1.26
11/76	0.25	-	-	-	0.25	-	-	1.92	1.42	-
12/76	-	1.08	0.34	-	0.25	1.28	-	2.84	1.73	-
Total 1976	0.84	1.62	1.34	0.25	4.26	1.45	3.67	8.19	8.29	2.69
1/77	-	-	-	-	-	4.88	-	10.88	1.75	3.70
2/77	-	0.26	-	-	-	2.58	-	12.35	1.25	0.33
3/77	0.17	0.41	-	1.25	1.84	-	-	1.91	0.76	-
4/77	-	1.20	-	0.25	0.33	-	-	2.00	0.08	0.50
5/77	-	0.67	0.42	0.42	1.17	-	-	1.33	1.73	0.20
6/77	-	0.08	-	-	0.92	-	0.75	1.91	0.42	-
7/77	-	0.08	-	2.91	0.42	-	-	1.33	1.73	0.20
8/77	-	-	-	2.17	0.25	-	-	1.48	8.51	0.32
9/77	-	-	0.59	-	5.25	-	-	8.32	2.20	0.25
10/77	-	1.47	0.25	1.24	0.91	-	-	1.75	0.16	-
11/77	0.20	-	0.17	-	1.65	0.92	-	3.25	0.17	-
12/77	2.34	-	-	5.00	1.01	0.88	-	1.97	-	-
Total 1977	2.71	4.17	1.43	13.24	13.75	9.26	0.75	53.49	18.47	15.30

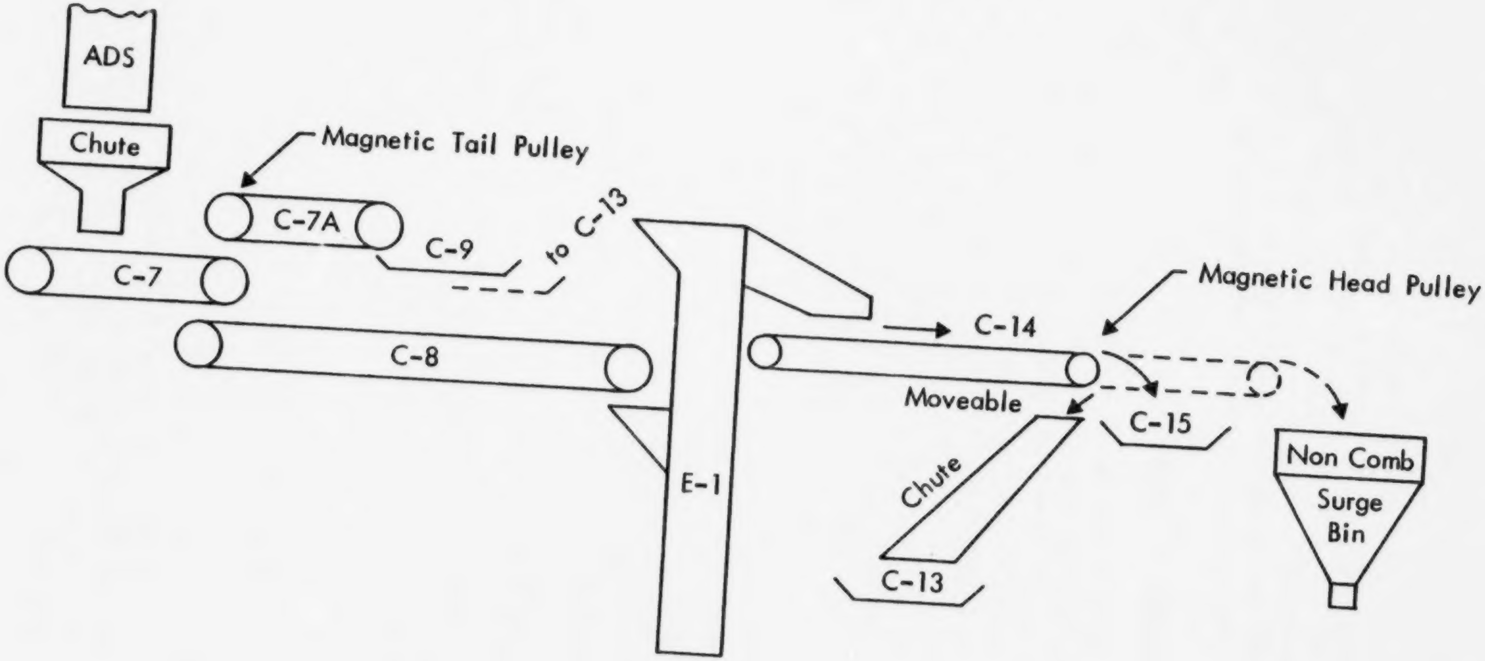

ADS
Chute
Magnetic Tail Pulley
C-7A
C-7
C-9
to C-13
C-8
E-1
C-14
Magnetic Head Pulley
Moveable
Chute
C-13
C-15
Non Comb
Surge
Bin

Figure 3. Flow stream following drop-out of ADS heavies.

Ferrous Metal Separation System

Ferrous metal is either separated on the tipping floor as large unprocessable items for direct sale as scrap or removed from the refuse by a Dings magnet following the first stage shredding. The first type is called nonprocessed ferrous. Additional ferrous removal is provided by magnetic pulleys in the conveying system for the ADS heavies. No major problems have been encountered with the ferrous removal system.

Aluminum Separation System

The aluminum separation system utilizes the concepts of high frequency eddy current rejection and represents a new technology. As such, the system has encountered a number of operating problems. These include: corrosion at the juncture of dissimilar metals; excessive cooling water requirements for the field magnets because of the lack of automatic cooling water flow controls and the absence of a closed loop system; and material pluggage due to small clearances between conveyors C-22 and C-23. A major end product problem was created by the simultaneous removal of nonferrous metal such as copper, zinc, and brass with the aluminum resulting in low purity of aluminum scrap. To solve this problem, an air knife was installed to aerodynamically remove aluminum in the form of flattened cans and other similar shapes. Additionally the magnets used in the eddy current separation of aluminum were damaged by freezing weather conditions during the preceding winter and were replaced during the summer. Even with these improvements, the systems were inoperable due to electrical problems resulting from the fire damage in November 1976 and did not operate during 1977. Work is continuing in an attempt to resolve the problems with the system.

Pneumatic Conveying System

The pneumatic conveying system (PSI) includes the PSI air-lock feeder, PSI blower, and 35.6-cm (14-in.) pipeline to the Atlas storage bin. As previously discussed, the pipeline was worn enough to necessitate two extended periods of downtime during which the entire pipeline (152 m, or 500 ft) was replaced.

Downtime data for the pneumatic conveying system are given in Table 3.

Atlas Bin

The performance of the Atlas bin was satisfactory in providing storage and feed to the boilers at the power plant. There were, however, major impacts on the operation of the Atlas bin. These impacts were the extreme wear of the floor and the bin fires, both of which were discussed in previous subsections.

TABLE 3. PNEUMATIC CONVEYING SYSTEM (PSI) DOWNTIME (1977)
(HR)

Date	Air-lock feeder	PSI - blower	Pipeline	PSI misc.
1/77	1.17	0.17	6.75	0.33
2/77	-	0.29	-	4.67
3/77	-	-	-	2.36
4/77	-	-	0.33	3.47
5/77	-	0.16	2.33	5.40
6/77	-	0.66	28.09	4.46
7/77	-	3.16	16.26	3.89
8/77	-	-	-	8.24
9/77	-	-	-	5.78
10/77	-	0.08	7.09	10.40
11/77	7.75	3.00	1.42	5.21
12/77	-	-	60.84	2.43
Total	8.92	7.52	123.11	56.64

PROCESSING PLANT PRODUCTION AND DOWNTIME

Refuse Processed and RDF Produced

The mass of refuse processed per month and the monthly production of RDF, ferrous metal, nonferrous metal, wood chips, baled paper, glass, grit, and rejects for 1976 and 1977 are given in Table 4. The RDF produced is by mass difference in incoming refuse less glass and grit, rejects, ferrous metal, nonferrous metal, and wood chips, and includes any process plant material losses. Input material from private vehicles is estimated based on the number of vehicles multiplied by an estimated average amount of refuse delivered per vehicle.

In 1976, 37,136 Mg of refuse were processed compared to 43,891 Mg in 1977. The maximum and minimum masses of refuse processed monthly in 1976 were 3,908 Mg in April and 1,743 Mg in November, respectively. The low mass in November was the result of the fire in the process plant which caused 2 weeks of downtime. Except for November, the lowest amount of refuse processed per month was 2,724 Mg in February. In 1977, the maximum and minimum monthly processing rates were 4,744 Mg in August and 2,144 Mg in February, respectively. Refuse-derived fuel and ferrous metal production as shown in Table 4 tend to vary directly with the mass of refuse processed. These trends are more apparent in Table 5, which gives the data from Table 4 in terms of percentages, and indicate a relatively consistent refuse composition profile for the system with respect to RDF and ferrous metal production. Production of nonferrous metals, baled paper, and wood chips have been at low levels, more variable, and on an intermittent, demand/availability basis. The generation of rejects has varied from 4.71 to 13.13%. Seasonal variation in refuse received appears similar for both years except for unusual events noted previously which caused refuse to be diverted to landfill. This comparison can be seen in Figure 4 along with RDF produced relative to refuse received.

The major problems which affected the plant production were a flood caused by frozen water pipes in January 1977, the Atlas bin floor repair in June, and the 35.6-cm (14-in.) pneumatic pipeline replacement in the process plant in both July and December which resulted in the diversion of incoming trucks to the landfill. The amount of refuse diverted was not scaled, but it is estimated that the amount diverted was 3,000 Mg. Table 6 shows the days on which refuse was diverted to the landfill and the events which made diversion necessary.

Processing Plant Run Time, Idle Time, and Downtime

The following is a definition of terms which are necessary for a complete understanding of the discussion in this section:

TABLE 4. MONTHLY REFUSE PRODUCTION BY WEIGHT (1976-1977)
(Mg)

Month (1976)	Raw refuse processed	Glass and grit	Rejects to landfill	Fe-metal	Non Fe-metal	Paper[a]	Woodchips	RDF (by difference)[b]
January	2,894.79	28.31	136.22	183.47	0.00	*	67.80	2,478.99
February	2,719.42	7.24	165.83	176.50	0.00	*	39.45	2,330.40
March	2,785.70	16.92	278.36	157.75	0.00	*	29.28	2,303.39
April	3,900.30	56.06	301.42	251.01	0.00	*	28.96	3,262.85
May	3,476.43	14.08	274.58	236.18	0.00	*	23.14	2,928.45
June	3,354.01	4.20	261.10	253.43	0.00	*	28.43	2,806.85
July	3,193.80	56.29	210.40	244.61	0.00	*	25.06	2,657.44
August	3,314.41	7.67	236.65	226.65	0.00	*	7.69	2,835.75
September	3,197.65	4.52	237.85	215.98	0.00	*	12.66	2,726.64
October	3,419.85	22.01	276.41	279.01	0.00	*	22.06	2,820.36
November	1,739.29	0.00	134.29	133.61	0.00	*	0.00	1,471.39
December	3,140.88	0.00	249.99	236.49	0.08	*	11.16	2,643.16
Total (1976)	37,136.53	217.30	2,763.10	2,594.69	0.08		295.69	31,265.67
(1977)								
January	2,352.90	*	243.53	95.56	1.98	0.00	0.00	2,011.83
February	2,956.16	*	225.65	187.85	0.00	13.60	6.15	2,522.91
March	3,791.23	*	305.67	285.83	0.33	0.00	15.06	3,184.34
April	3,761.82	*	239.87	275.06	0.00	0.00	15.61	3,231.28
May	3,921.94	*	332.09	240.05	0.00	0.00	3.00	3,346.80
June	2,657.20	*	217.61	178.12	0.00	15.78[c]	0.00	2,245.69
July	3,520.13	*	370.85	217.85	0.00	0.00	5.71	2,925.72
August	4,733.73	*	621.50	313.61	6.20[d]	12.93	10.61	3,768.88
September	4,523.12	*	580.62	315.41	0.00	5.46	0.00	3,621.61
October	4,467.67	*	351.62	264.38	0.00	13.61[e]	0.00	3,838.06
November	3,825.92	*	182.47	244.14	0.00	0.00	0.00	3,399.31
December	3,300.00	*	221.49	111.46	0.00	7.29	0.00	2,959.76
Total (1977)	43,811.82		3,892.97	2,729.37	8.51	68.67	56.14	37,056.16
Total (1976-77)	80,948.35	217.30	6,656.07	5,324.06	8.59	68.67	351.83	68,321.83
% of Total	100%	.27%	8.22%	6.58%	.01%	.08%	.43%	84.40%

[a] Asterisks (*) indicate no identification was made for that month.

[b] RDF by difference is incoming raw refuse less paper, rejects, Fe-metal, non Fe-metal, and woodchips. Therefore, the RDF by difference also includes any plant material losses.

[c] Includes 9.25 Mg cardboard.

[d] Aluminum.

[e] All cardboard.

TABLE 5. MONTHLY REFUSE PRODUCTION BY PERCENTAGE (1976-1977)

Month (1976)[a]	Raw refuse processed	Glass and grit	Reject to landfill	Fe-metal	Non Fe-metal	Paper[b]	Woodchips[b]	RDF (by difference)[c]
January	100	0.98	4.71	6.34	0.00	*[d]	2.34	85.63
February	100	0.27	6.10	6.49	0.00	*	1.45	85.69
March	100	0.61	9.99	5.66	0.00	*	1.05	82.69
April	100	1.44	7.73	6.44	0.00	*	0.74	83.65
May	100	0.41	7.90	6.79	0.00	*	0.67	84.23
June	100	0.13	7.78	7.55	0.00	*	0.85	83.69
July	100	1.76	6.59	7.66	0.00	*	0.78	83.21
August	100	0.23	7.14	6.84	0.00	*	0.23	85.56
September	100	0.14	7.44	6.75	0.00	*	0.40	85.27
October	100	0.64	8.08	8.16	0.00	*	0.65	82.47
November	100	0.00	7.72	7.58	0.00	*	0.00	84.60
December	100	0.00	7.96	6.53	0.003	*	0.36	84.15
Average[e] (1976)	100	0.39	7.44	6.99	0.0002		0.79	84.19
(1977)								
January	100	*	10.35	4.06	0.08	0.00	0.00	85.51
February	100	*	7.63	6.35	0.00	0.46	0.20	85.36
March	100	*	8.06	7.54	0.00	0.00	0.40	84.00
April	100	*	6.38	7.31	0.00	0.00	0.41	85.90
May	100	*	8.47	6.12	0.00	0.00	0.08	85.34
June	100	*	8.19	6.70	0.00	0.59[f]	0.00	84.52
July	100	*	10.53	6.19	0.00	0.00	0.16	83.11
August	100	*	13.13	6.63	0.13	0.27	0.22	79.62
September	100	*	12.84	6.97	0.00	0.12	0.00	80.07
October	100	*	7.87	5.92	0.00	0.30[g]	0.00	85.91
November	100	*	4.77	6.38	0.00	0.00	0.00	88.85
December	100	*	6.71	3.38	0.00	0.22	0.00	80.69
Average[e] (1977)	100		8.89	6.23	0.02	0.16	0.13	84.58
Average %	100	.27	8.22	6.58	.01	.08	.43	84.40

[a] Due to fire, the plant processed only 2 weeks in November of 1976.

[b] Woodchips and baled paper are produced as the supplies become available.

[c] RDF by difference is incoming raw refuse less paper, rejects, Fe-metal, non Fe-metal, and woodchips. Therefore, the RDF by difference also includes a plant material losses.

[d] Asterisks (*) indicate no identification was made for that month.

[e] Average percent is calculated from total weight and is not an average of the individual months.

[f] Includes 0.35% cardboard.

[g] All cardboard.

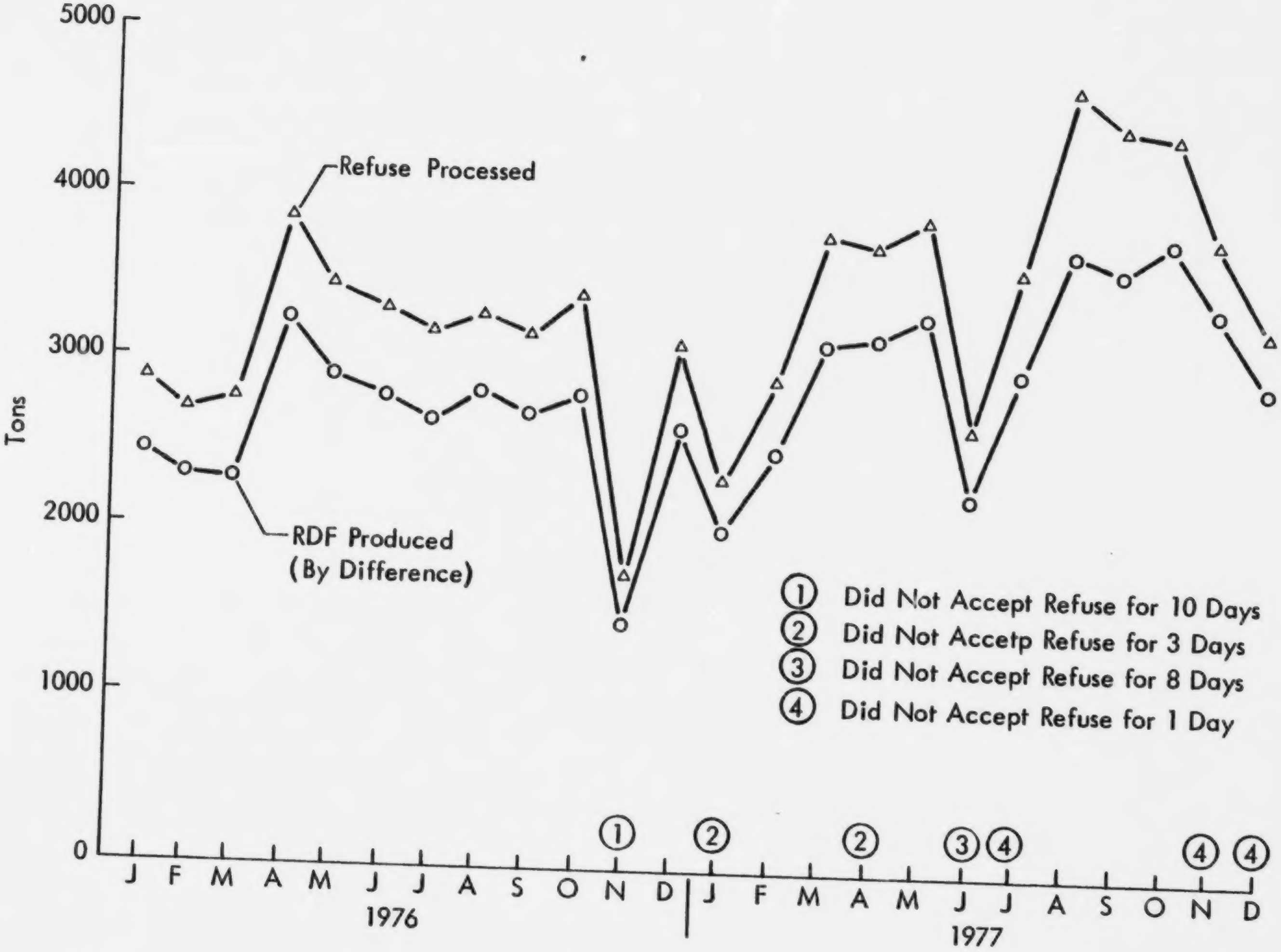


Figure 4. Mass of refuse processed and RDF produced - 1976-1977.

TABLE 6. DAYS REFUSE DIVERTED TO LANDFILL (1977)

Date	Cause	
January 3	Pipes froze in process area.	Flooded basement due to ruptured pipe.
January 4	Pipes froze in process area.	
January 5	Pipes froze in process area.	
April 12	Power plant yearly maintenance on No. 5 and No. 6 bins.	
April 13	Power plant yearly maintenance on No. 5 and No. 6 bins.	
April 14	Power plant yearly maintenance on No. 5 and No. 6 bins.	
June 3	Changing PSI line.	
June 4 (Saturday)	Changing PSI line.	
June 6	Changing PSI line.	
June 7	Changing PSI line.	
June 20	Replacing Atlas bin floor.	
June 21	Replacing Atlas bin floor.	
June 22	Replacing Atlas bin floor.	
June 23	Replacing Atlas bin floor.	
June 24	Replacing Atlas bin floor.	
July 15	Fire in Atlas bin.	
November 18	Fire in Atlas Bin.	
December 13	PSI line.	

- Systems run time: Process plant processes refuse and transfers RDF to Atlas bin for storage.

- System idle time: Process plant cannot process due to cause other than failure of process plant equipment (e.g., Atlas bin is full, repairs being made to Atlas bin, etc.).

- System downtime: Process plant cannot process due to equipment failure at process plant.

The processing plant system run time, idle time, and downtime are shown in Figure 4. The total hours of potential running time per month are shown as a reference.

The major periods of idle time and their causes were:

Month and Year	Cause
November 1976	Process plant fire.
January 1977	Process plant water pipe ruptured.
June 1977	Repair and replacement of a section of pneumatic line and repair of Atlas bin floor.
July 1977	Atlas bin fire.

Process plant total operating hours and subsystem downtime are shown in Figures 5 through 7 and are for each 6-month period from July 1976 through December 1977. A slight decline in operating hours is noted. Since the plant has only one process line, shutdown of any subsystem results in a plant shutdown.

Shredder subsystem downtime is primarily caused by jamming of the Z-pan infeed conveyor (C-1) feeding the first shredder. Downtime for the ADS subsystem was the highest of any subsystem and remained highest for the 18-month period. Processing of wet refuse tends to increase plugging of the ADS subsystem which contributes to downtime. It also requires resetting the blower inlet vanes to operate at a lower air flow rate.

Little mechanical difficulty was encountered in the operation of the ferrous metal removal subsystem. Downtime was due to unplugging the discharge chute of the C-13 conveyor which drops ferrous metal into the parked semi-trailer. Tipping floor downtime was mainly due to removing wire and other debris from the wheels and axles of the end loader. Downtime for the PSI pneumatic transport line to the Atlas bin increased over each of the time periods. This downtime was due to replacement of pipeline sections in two time periods. The balance of the downtime was due to problems caused by the worn line prior to its replacement.

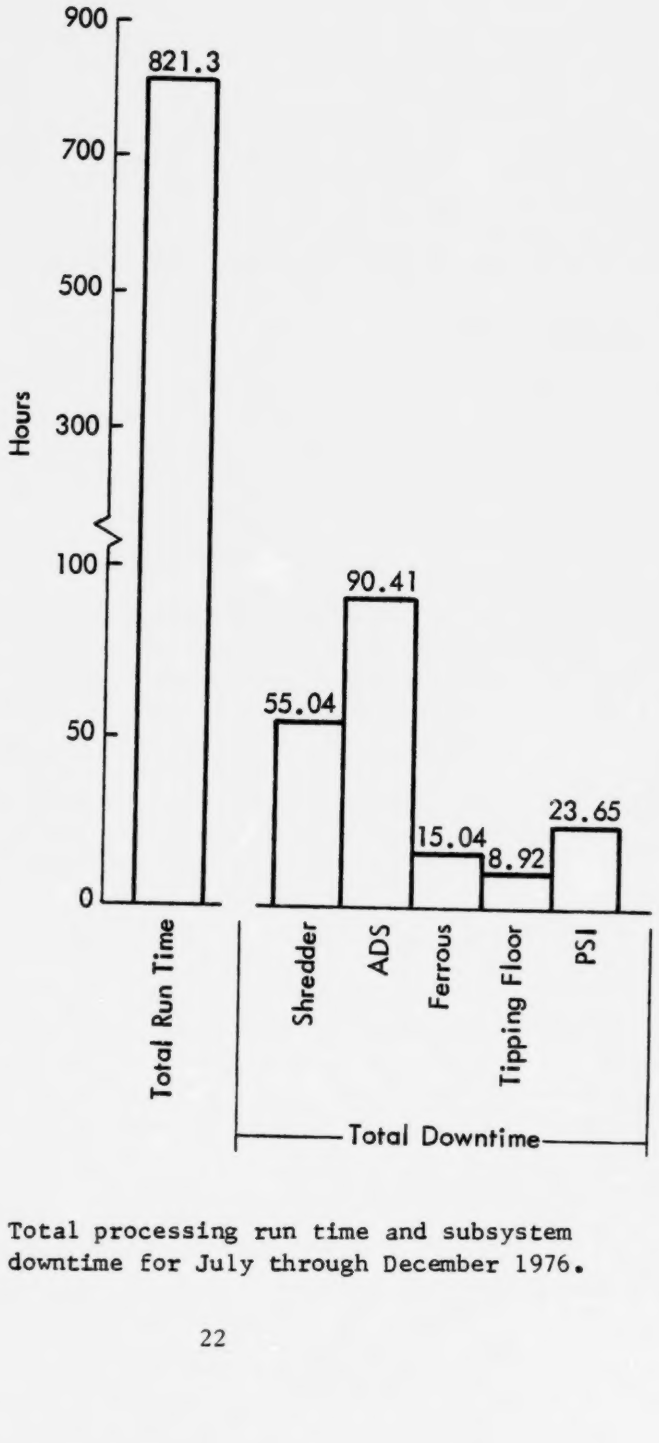


Figure 5. Total processing run time and subsystem downtime for July through December 1976.

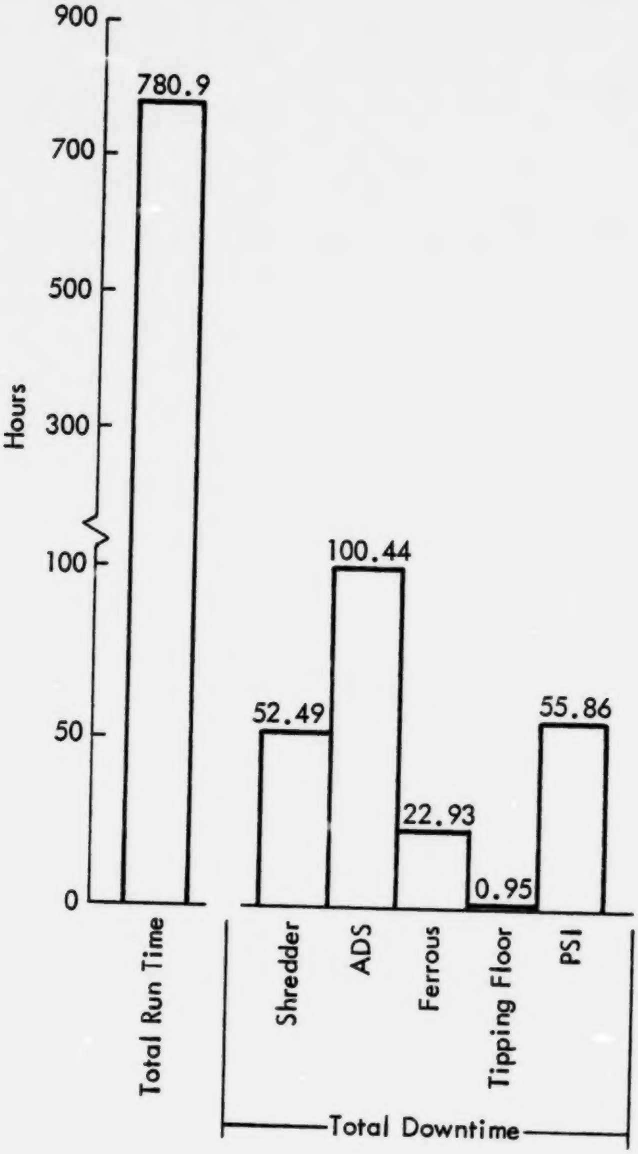


Figure 6. Total processing run time and subsystem downtime for January through June 1977.

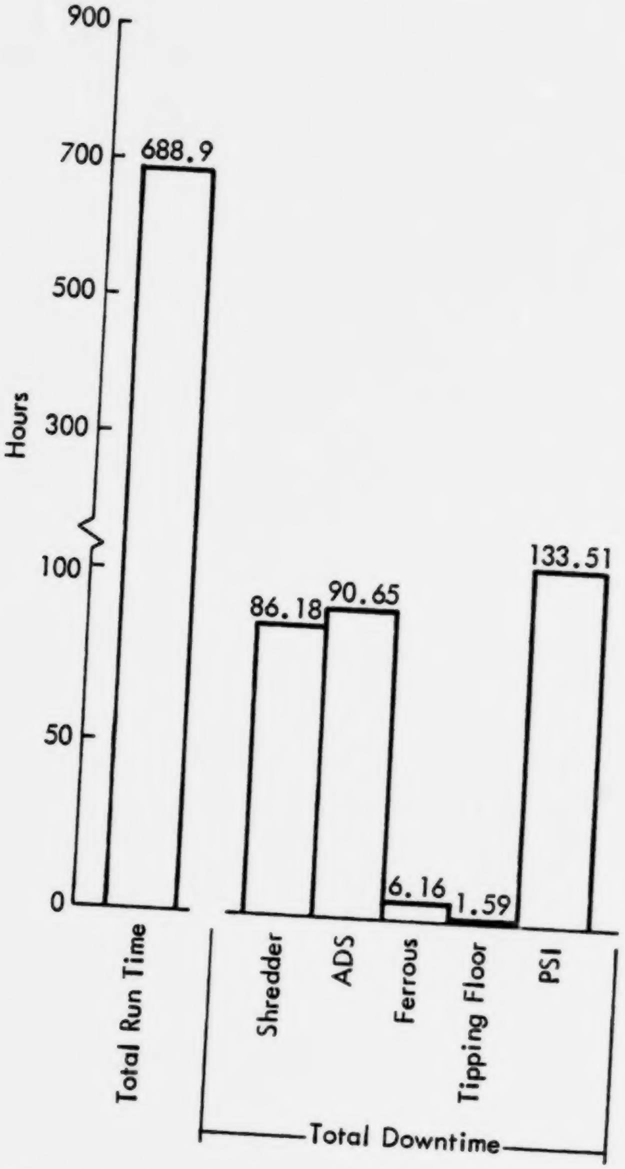


Figure 7. Total processing run time and subsystem downtime for July through December 1977.

ELECTRIC POWER UTILIZATION

Electric power consumption was recorded for the solid waste plant, Atlas storage bin, and major items of processing equipment for the entire year of 1977.

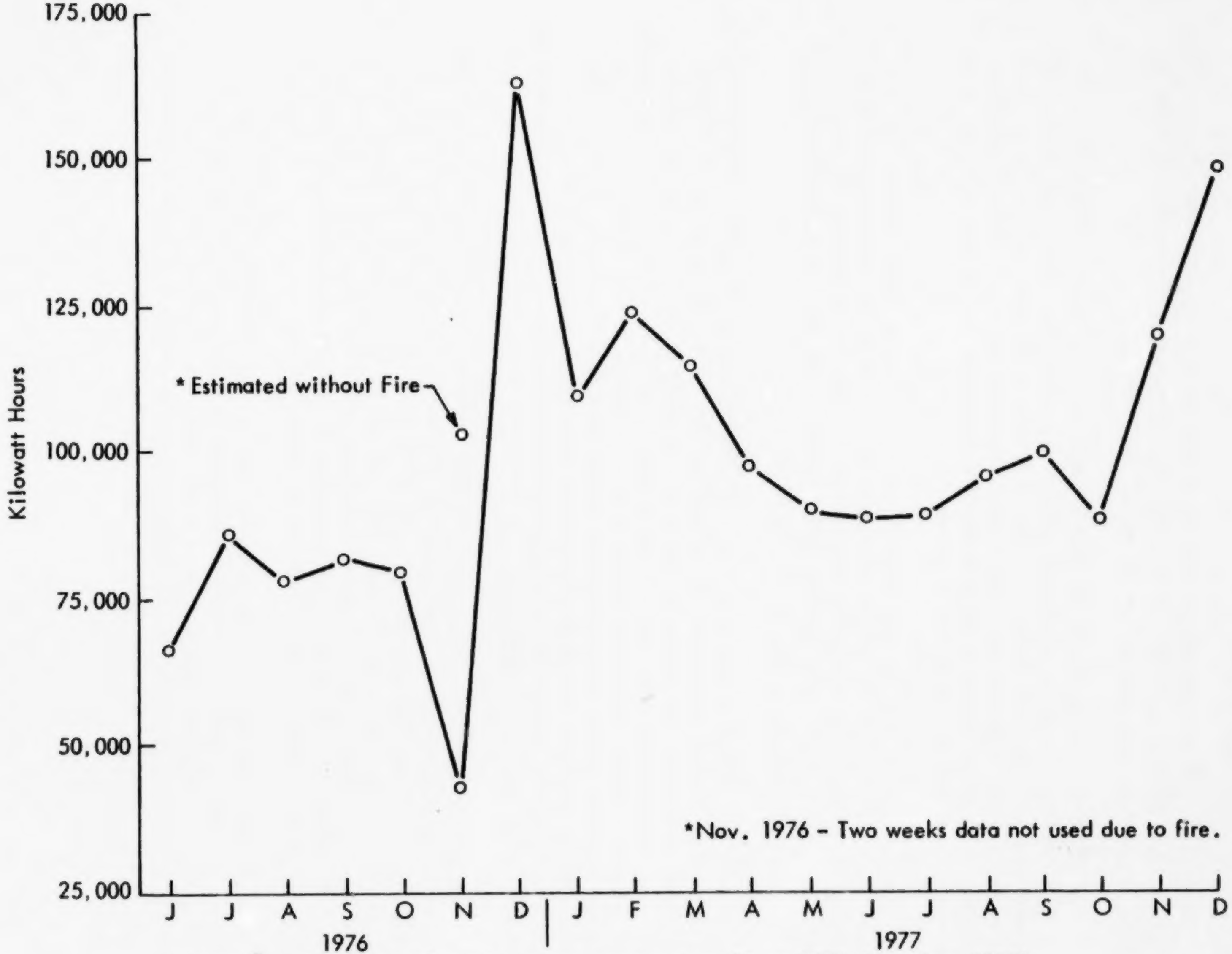
To facilitate comparison by subsystems, electric power consumption is shown according to major subsystem usage. The category "total indirect plant" refers to electrical heating, air conditioning, lighting, ventilation, the conveyors, Dings magnet, air compressor, building service, and all other systems not listed under a major subsystem heading.

The amount of electrical energy used depends upon several factors, including the amount of refuse processed and plant heating (processing area plus offices and control room) or air conditioning (office and control room areas only) required.

Indirect energy requirements are by far the largest factor comprising 46% of the total energy consumed and exceeding the combined total of shredding, ADS, and pneumatic conveying to the Atlas storage bin. If the Atlas storage bin requirements are also considered indirect and new subtotals are computed, the indirect energy consumed would be 63% of total system requirements. Indirect electric power consumption is shown on a monthly basis in Figure 8. The processing plant electric resistance heating is apparently a large consumer of electric power because significant increases in indirect consumption occur during the winter months.

Shredding required the second largest amount of electrical energy. Secondary shredding required approximately 60% more electrical energy than did primary shredding. The additional size reduction achieved in the smaller than 38 mm (1.5-in.) range was 37%, but the imbalance in electrical energy of 37% between the primary and secondary shredders indicates the need to better balance the grate sizing to achieve the desired product size and a relatively even distribution of electrical power consumption.

Electrical energy requirements for pneumatic conveying and storage are 22% of the total electric power consumption. Electric power consumers in the Atlas storage bin include the two bin sweep conveyors, four drag conveyors (two in use in 1977), fluffing rolls and rotary air lock feeders for each drag conveyor, and blowers for each of the four feed lines (two in use in 1977).



*Nov. 1976 - Two weeks data not used due to fire.

Figure 8. Indirect electric power consumpton (June 1976-December 1977)

Figures 9, 10, and 11 show subsystems' quarterly electrical energy usage, on a percentage basis, from July 1976 through December 1977. Seasonal variations in energy requirements particularly the indirect energy consumption, can be seen.

Electrical energy requirements per megagram of refuse processed for 1977 averaged 62 kWh based on 43,811 Mg processed compared to 71 kWh based on 23,360 Mg processed for June through December 1976.

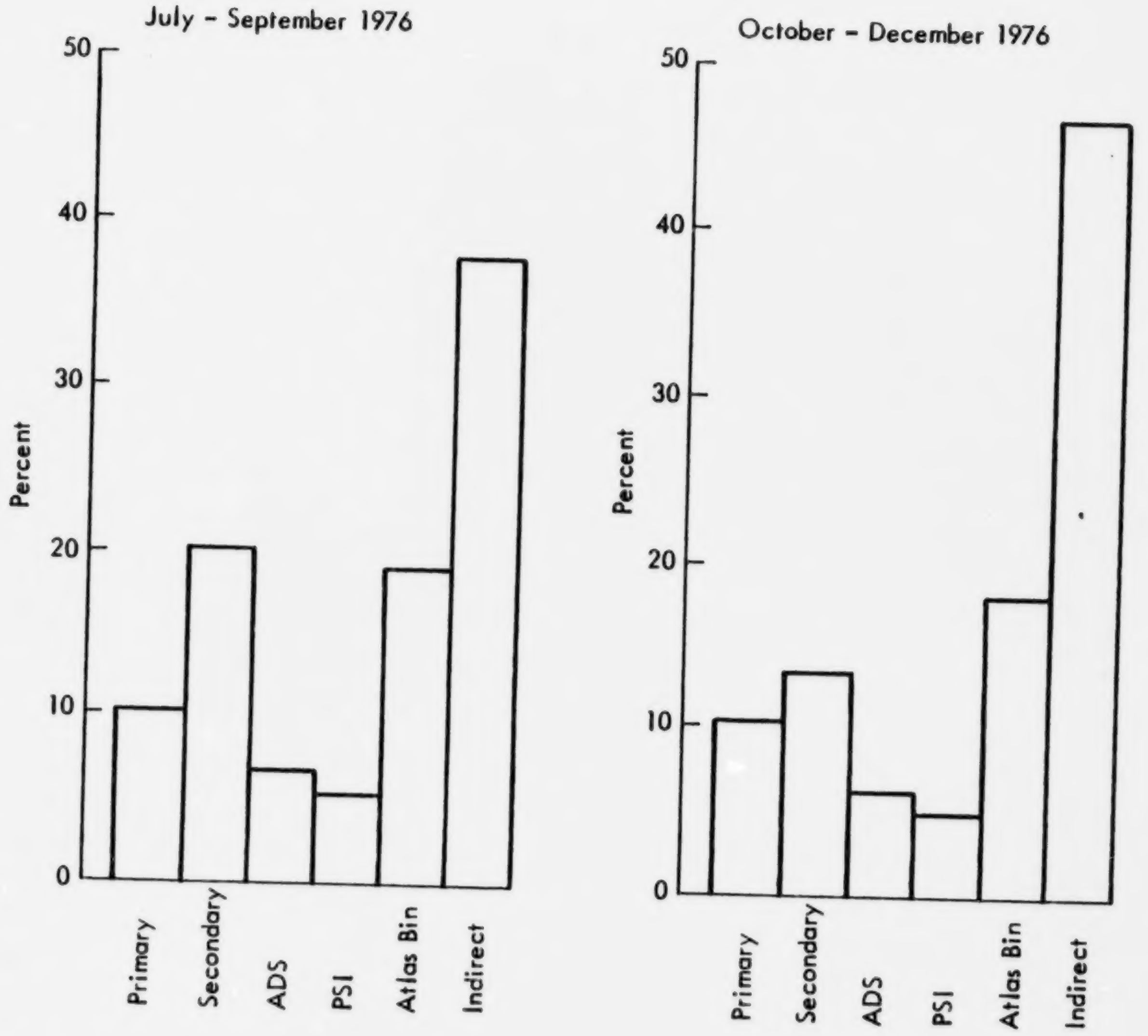


Figure 9. Quarterly subsystem energy consumption (July-December 1976).

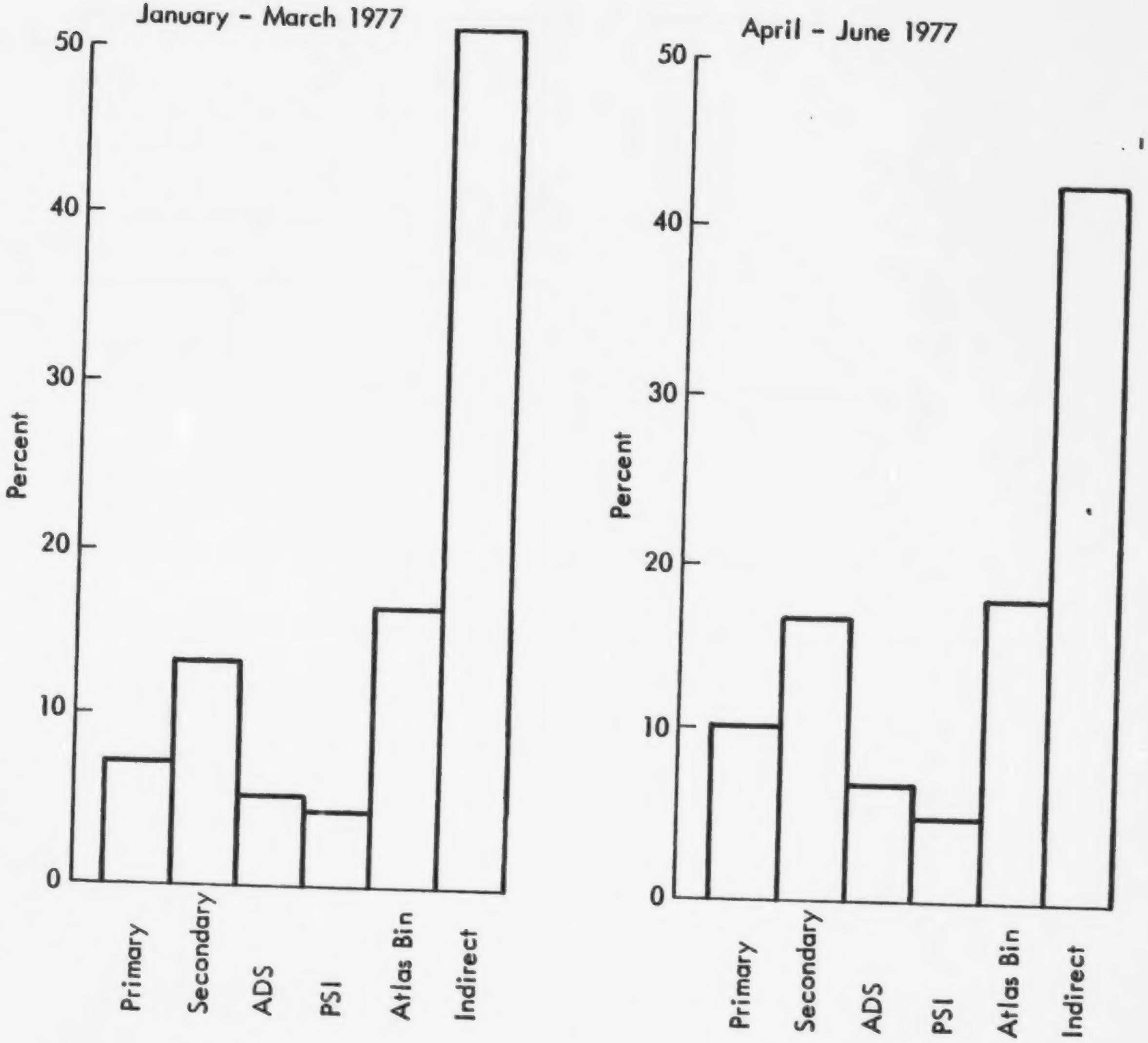


Figure 10. Quarterly subsystem energy consumption (January-June 1977).

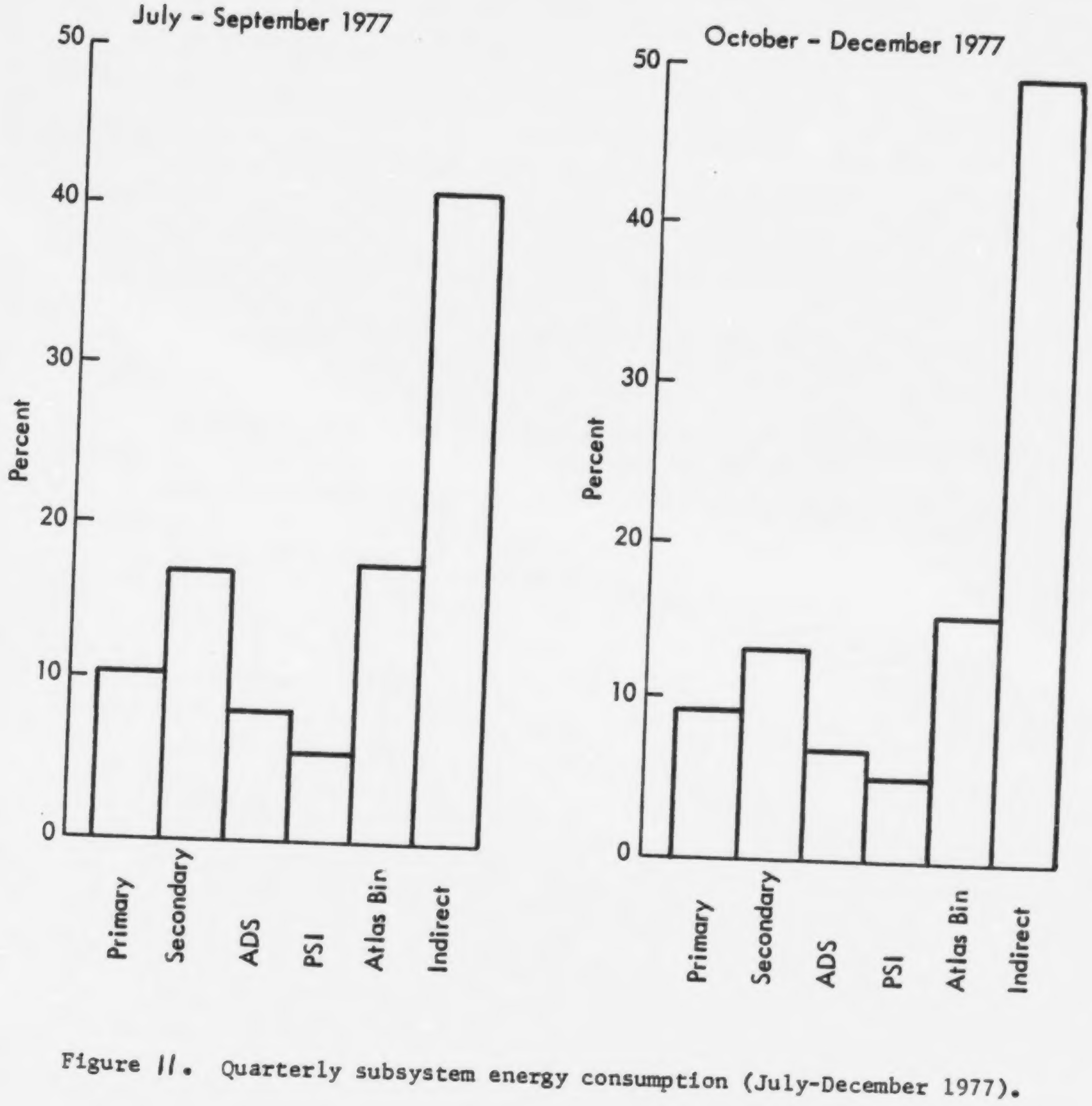


Figure 11. Quarterly subsystem energy consumption (July-December 1977).

SECTION 3

ECONOMIC EVALUATION

This section presents an economic evaluation of the Ames Solid Waste Recovery System for 1977, its second full calendar year of operation. An economic evaluation of the system's first full calendar year of operation (1976) was presented in the first year report (1). This evaluation addresses the economics of the overall operation of the solid waste system and the individual subsystems. Cost comparisons are made of the 1977 and 1976 operations; however, some categories of data collected in 1977 such as labor distribution and electric power consumption, were not complete for all of 1976. The economic evaluation study originated in June 1976; therefore, the expense analysis for each subsystem includes only the period June through December 1976 for comparison to 1977.

TOTAL SYSTEM

The experience gained in the first year of operation (1976) resulted in a reduction of overall operating expenses during 1977. While some costs were obviously reduced (e.g., lower overall costs), others actually increased. Those costs which increased were electrical energy and replaced parts primarily as a result of general economic inflation. Operating and maintenance expenses as reported on a monthly basis varied widely. This was primarily the result of randomly occurring equipment repair charges and the cash accounting system used which does not recognize expenses until they are paid.

A listing of initial capital expenditures totaling $6.3 million is given in Table 7. Initial capital investment for the refuse processing plant alone is detailed in Table 8, and the capital costs of the storage bin and pneumatic transport system are shown in Table 9.

The total plant expenses during 1977 were $992,270. This amount includes depreciation and interest on the capital expenditures and the refuse processing operational costs. Total revenue was $498,626 which was derived from the sale of RDF, metals, wood chips, and paper; fees charged for commercial and private haulers; and reimbursements and refunds.

TABLE 7. COMPARISON OF PLANNED AND ACTUAL COSTS

Capital investment	Estimated	Actual
Processing plant	$3,898,000	$4,084,307
Pneumatic conveyors	150,000	164,388
Storage bins	687,000	551,292
Electric work	114,000	314,020
Boiler modification	179,000	178,988
Land	156,000	108,068
Engineering	275,000	376,896
Subtotal	5,459,000	5,777,959
Minor equipment and start-up	100,000	486,405
Total investment	$5,559,000	$6,264,364

TABLE 8. INITIAL CAPITAL INVESTMENT FOR REFUSE PROCESSING PLANT

Equipment	Cost
Shredders, five conveyors associated with shredders and ferrous metal separator	$ 373,382
Air density separator system	182,854
Pneumatic conveying system to storage bin	30,017
Raw refuse scale system	32,769
Plant conveyors other than five units associated with the shredders	104,600
Nonferrous metal separation system	251,130
Plant hoist to move equipment	24,520
Electric substation including 4,160-v transformer	44,636
Motor starters and electric disconnector for 4,160-v motors	52,707
Total equipment	$1,096,615

Building and apparatus	Cost
Excavation, foundation, concrete, and plant building	1,515,589
Reinforcing steel	250,934
Masonry	5,727
Miscellaneous metal	164,768
Carpentry	20,534
Doors and frames	23,112
Mechanical	414,105
Electrical	314,020
Total building and apparatus	2,708,789
Engineering	278,903
Total capital cost, refuse processing plant	$4,084,307

TABLE 9. INITIAL CAPITAL INVESTMENT FOR STORAGE BIN AND TRANSPORT SYSTEM

Storage bin structure and reclaiming system	$ 413,350
Storage bin foundation and construction	243,080
Pneumatic conveying line excavation and concrete pit (between the process plant and the bin)	14,300
Electrical system and equipment	314,070
Electrical power substation	38,800
Engineering fee	98,000
Pneumatic equipment from the process plant to bin	30,020
Piping from process plant to storage bin	12,900[a]
Pneumatic to boiler equipment	60,035[b]
Mechanical including pipes and elbows	94,245[b]
Total	$1,308,800

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[a] Based on June 1977 overall cost of pipe change at $24.51/ft with two-fold 10% inflation adjustment for the 650-ft pipe.

[b] Since only two of the four pneumatic systems were utilized, half of the total actual investment was used for depreciation purposes.

The amount of refuse processed in 1977 was 43,891 Mg (48,381 tons). Based on this amount the net cost for processing the refuse was $13.90/Mg ($12.61/ton). The calculations are shown in Table 10.

METHODS OF CALCULATION

As mentioned above, the City of Ames uses a cash accounting system which recognizes expenses when they are paid. This cost accounting method occasionally results in extreme fluctuations in expenses. Figure 12 shows the correlation between revenues and refuse received and between expenses and refuse received. Since the monthly expenses reported did not reflect actual expenses for 1977, they were reviewed and adjusted at the end of 1977 to show actual expenses.

Capital costs used in this economic evaluation differ from those used by the City of Ames and are based on straight line depreciation as determined from Internal Revenue Service guidelines plus total interest averaged over the 20-year period of indebtedness (1). Since the City of Ames issued revenue bonds for capital financing, depreciation is not an identifiable line item in budget expense. Actual capital costs are represented by principal and interest payments on bonds.

SUBSYSTEM ECONOMICS (JUNE 1976 to NOVEMBER 1977)

The overall initial cost structure for the Ames Solid Waste Recovery System was discussed in the preceding section. Operating revenues will be presented in the subsection, "Break-even Analysis." This section presents a detailed cost analysis of major subsystems in the processing plant and in the storage and retrieval system.

Major subsystems of the processing plant which are discussed are tipping floors, shredding, ads, and ferrous metal separation, as well as an "other" category which includes the nonferrous separation system.

Tipping Floor

The concrete floor and tipping floor room are considered part of the overall plant construction. Primary equipment includes an end loader and a floor sweeper. During 1976, the floor sweeper was leased at $200 per month. The end loader cost was $7.50/hr. Both of these costs include maintenance and fuel. The cost, excluding indirect cost ((2), p. 52) of processing refuse on the tipping floor was $1.29 per Mg of refuse received.

TABLE 10. NET OPERATING EXPENSE PER MEGAGRAM REFUSE PROCESSED (1977)

Operating costs for 1977:

Refuse processing	$ 615,679.60
Depreciation	332,206.00
Interest	160,720.00
Gross operating expenses	$1,108,605.60

Operating revenues for 1977:

Gross operating revenues:	$ 498,626

Net operating expenses = $1,108,605.60 - 498,627.00 = $609,978.60

Total refuse processed in 1977: 43,890 Mg (48,380 tons)

Net operating expense per Mg of refuse processed:

$$\frac{\$609,978.60}{43,890\ \text{Mg}} = \$13.90/\text{Mg}\quad (\$12.61/\text{ton})$$

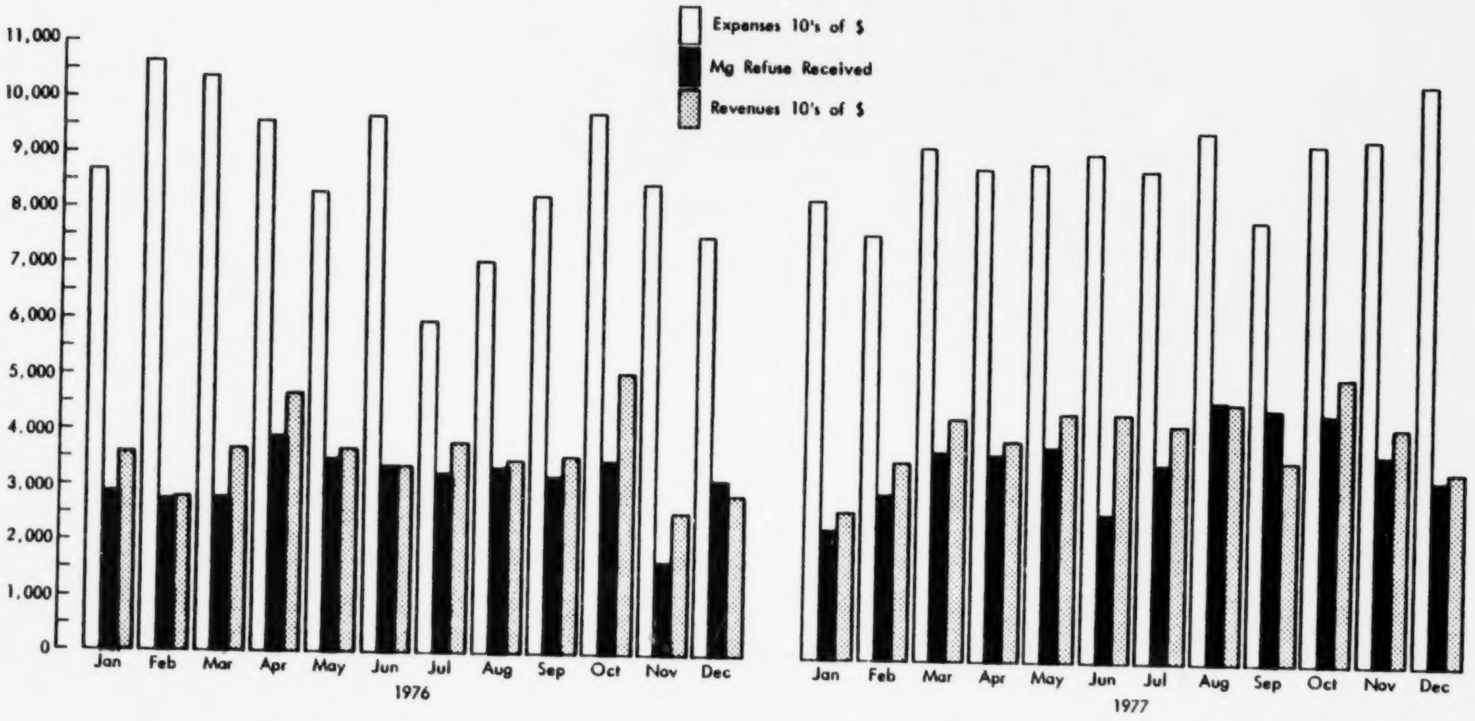

Figure 12. Revenues and refuse received (1976-1977).

Shredding

The shredding system includes two shredders arranged in series plus conveyors which feed the first shredder and carry material between the shredders and out of the second shredder to the air density classification system.

The shredding system was installed at a total initial cost of $373,382. The primary and secondary shredders consume 11 and 16%, respectively, of total electrical power of the processing plant. Hammers for the primary shredder cost $124 each; and for the secondary, $47 each, resulting in a cost for replacing complete sets of $5,952 and $2,526, respectively. Costs during the period June through November 1976 were distributed as shown in Table 11.

It was determined that 97% of direct labor associated with conveyors C-1, C-2, C-3, and C-6 consisted of walking beside the conveyors and watching for hazardous materials and events. The other 3% was spent unplugging congested conveyors. Labor charged to shredders included changing hammers, welding (to rebuild) primary shredder hammers, and maintenance during processing time.

The cost of processing refuse through this subsystem is $2.14/Mg ($1.95/ton).

ADS System

The ADS subsystem consists of a surge bin; flight conveyor; ADS chamber and fan; oscillating conveyor; cyclone; conveyors C-7, C-8, C-14, and C-15; and bucket elevator E-1.

A cost summary for the ADS system is given in Table 12. Approximately 29% of the total expense was attributed to labor in monitoring conveyors C-7, C-8, C-14, and C-15. Some of this could be eliminated through the use of additional closed circuit television cameras in these areas. The total cost of operating the ADS subsystem was $0.37/Mg ($0.34/ton).

Ferrous Metal Separation System

Ferrous metal separation occurs in two ways. Nonprocessed ferrous metals are derived from heavy items such as stoves, refrigerators, lawn mowers, and automotive parts. These are separated on the tipping floor immediately when they enter the plant. Processed ferrous metal is removed by a magnetized belt and two magnetic pulleys. The magnetized belt is located between the first and second shredders, and approximately 90% of retrieved ferrous metal is removed first at this point. The second removal of ferrous metal occurs at the bottom of the ADS chamber. The third removal takes place before the heavy fraction leaves the ADS subsystem and enters the storage bin for material classified as nonferrous rejects. All separated ferrous metal is carried by

TABLE 11. SHREDDING SYSTEM COSTS (JUNE-NOVEMBER 1976)

Expense source	Variable expense	Fixed expense	Percentage of total expense
Conveyors			
C-1	$ 263.33	$320.45	
C-2	473.64		
C-3	381.69		
C-6	375.01		
Conveyor total	$ 1,493.67	$320.45	4.6
Primary Shredder			
Supplies	$ 1,572.20		
Electrical power	3,801.03		
Hammers[a]	11,904.00		
Primary shredder total	$17,227.23		43.9
Secondary Shredder			
Supplies	$ 1,905.78	$301.99	
Electrical power	6,529.69		
Hammers[a]	4,512.00		
Secondary shredder total	$12,947.47	$301.99	33.8
Direct Labor			
Conveyors (917 hr)	$ 4,695.04		
Shredders (440 hr)	2,252.80		
Direct labor total	$ 6,947.84		17.7
Total Expense	$38,616.21	$622.44	100.0
Total cost = $39,238.65			

[a] Primary and secondary shredder hammers changed twice. Fixed costs are depreciable expenses.

TABLE 12. AIR DENSITY CLASSIFICATION SYSTEM COSTS (JUNE-NOVEMBER 1976)

System	Expense	Percentage of total expense
Flight Conveyor		
Supplies	$1,982.55	
Direct labor (292.25 hr)	1,511.68	
Total	$3,494.23	50.65
ADS Blower		
Supplies	$ 95.49	
Electrical power (8.65%)	2,386.17	
Total	$2,481.66	35.97
Cyclone		
Supplies	$ 454.08	
Direct labor (51 hr)	261.12	
Total	$ 715.20	10.37
Twin Screw Feeder		
Direct labor (40.50 hr)	$ 207.36	
Total	$ 207.36	3.01
Total for System	$6,898.45	100.00

belt conveyors to a semitrailer. Trailers are hauled two at a time over distances of up to 640 km (400 miles) to points where the metal is sold for commercial processing.

The two ferrous metal separation subsystems have their own mass flow, cost, and revenue data (Tables 13 and 14). For nonprocessed ferrous metal removed at the tipping floor, direct cost and revenue for the period June through November 1976 averaged \$10.59/Mg and \$20.90/Mg, respectively (2). Cost and revenue for processed ferrous metals were \$18.45/Mg and \$37.53/Mg, respectively. During this period, 171.6 Mg of ferrous metal were removed on the tipping floor, and 1,292 Mg were removed by the magnetic separation process.

Costs associated with processed ferrous metal result from shipping, labor, and supplies. It is significant that shipping accounts for nearly 97% of the cost of processing ferrous metal. Large fluctuations in the selling price per Mg have also been noted. These facts suggest re-examination of selling policies and shipping methods.

Of the total incoming refuse, processed metals cost approximately \$1.27/Mg (\$1.15/ton). Because of a relatively low amount of incoming refuse, nonprocessed metals cost only \$0.10/Mg (\$0.09/ton) of total incoming refuse.

Other Subsystems

The nonferrous separation subsystem classifies heavy, primarily noncombustible material from the ADS system into the following categories: aluminum, other nonferrous (brass, copper), glass, rejects, and oversized material. Heavy materials are also sorted by size by means of a large trommel screen into objects with sizes of 9.5, 25.4, 102 (3/8, 1, 4 in.), and oversized. Each type of material is stored in a large bin. This system has not operated on a continuous basis, and the only significant revenue (\$555) received was for 1.68 Mg of aluminum. The cost of hauling the rejected materials to the landfill was \$2.83/Mg of reject material.

The nonferrous separating system required an initial investment of \$251,130, but several technical operating problems have prevented operation of the aluminum separation equipment. Aluminum separation is achieved using a high frequency (960 Hz) alternating repulsive magnetic field to propel aluminum from a belt. Some aluminum cannot be separated from ferrous metal because it is directly attached to it, as in the case of a steel can with aluminum ends.

TABLE 13. FERROUS METAL REVENUES (JUNE-NOVEMBER 1976)

	Metals sorted at tipping floor			Metals processed			Total revenue from both dollars	% of Total revenue	
Month	2,000 lb/ton (tons)	Ton ($)	Total dollars	2,240 lb/ton (tons)	Ton ($)	Total dollars		From tipping floor	Processed
June	55.10	20.00	1,102	204.42	40.73	8,326	9,428	11.69	88.31
July	21.10	20.00	422	233.37	40.75	9,510	9,932	4.25	95.75
August	39.75	20.00	795	197.20	40.00	7,888	8,683	9.16	90.84
September	7.25	20.00	145	274.82	35.63	9,792	9,937	1.46	98.54
October	44.95	20.00	899	244.26	35.00	8,549	9,448	9.52	90.48
November	20.90	10.00	209	116.83	35.00	4,089	4,298	4.86	95.14
TOTAL	189.05		3,572	1,270.90		48,154	51,726	6.91	93.09

TABLE 14. PROCESSED AND NONPROCESSED FERROUS METAL EXPENSES (JUNE-NOVEMBER 1976)

	Processed metals				Tipping floor metals (nonprocessed)					
					Labor ($)		Eq. rent ($)			
Month	Shipping ($)	Supply ($)	Labor ($)	Total ($)	Truck driver	End loader	End loader	Truck	Supply ($)	Total ($)
June	3,845.59		123.42	3,969.01	162.00	81.51	93.19	320.00	-	656.70
July	3,807.11		36.30	3,843.41	117.45	77.08	88.13	-	-	282.66
August	4,324.63		317.02	4,641.65	188.33	75.11	85.88	-	-	349.32
September	4,690.56	Magnet gauge 70.73	24.20	4,785.49	76.95	67.24	76.88	-	-	221.07
October	3,263.23	Truck-purch. 10.00	108.90	3,382.13	62.78	71.50	81.75	-	-	216.03
November	2,405.94		24.20	2,430.14	20.25	33.78	38.63	-	-	92.66
Total	22,337.06	80.73	634.04	23,051.83	627.76	406.22	464.46	320.00	0	1,818.44
% Total Expenses	96.97	0.35	2.75	100.00	34.52	22.34	25.54	17.60	0	100.00

Several other items of processing equipment are operated independently of the main processing plant. A log chipper (an initial cost of $32,319) is kept in a corner of the tipping floor. It is used to grind presawed logs (from tree removal) into wood chips. Wood chips are sold for $14.87/ton for use in flower bedding. A total of 72.6 Mg (80 tons) of wood chips was sold between June and November of 1976 for $1,063. Expenses during this period included $375 for labor, $600 for trailer rental (to store wood chips), and $493 for supplies, maintenance, and repair, of which $119 was spent for reteething the log chipper ((2), pp. 77-78). A paper baler was purchased and installed for $85,877; it began operating in October 1976. It is located in a room that was added to the initial process plant building. Total sales of baled paper in 1977 amounted to $7,652 for 107 Mg. An average of 8.92 Mg of baled paper was processed each month. Average revenues were $71.51/Mg ($64.85/ton).

COMPARISON OF SUBSYSTEM COSTS

Process Plant

When evaluating operational economics of a complex system, it is important to examine each subsystem on a comparative basis and as a contributor to the total system economy. Table 15 lists the individual subsystem costs associated with processing each megagram of refuse entering the plant. Each subsystem's cost represents capital cost, materials, supplies, labor, electrical power, and maintenance.

The capital cost of the building and process equipment is clearly the greatest cost of operating the process plant. The shredder system, tipping floor, indirect labor, and the processing of ferrous metal are also large contributors.

Incremental analysis is useful in planning a system and in allocating resources for improvement. Table 16 provides a breakdown of subsystem costs allocated for labor during 1977. Several significant trends are evident. With respect to labor (including operations and maintenance on both regular time and overtime), cleaning the process plant is the largest cost, at 20%, followed by end loader operations and conveyors. Direct labor costs during 1976 and 1977 were as follows:

Year	Avg h/month	Avg Mg/month	h/Mg
1976	1,873	3,051	0.62
1977	2,313	3,657	0.63

TABLE 15. SUBSYSTEM COSTS OF PROCESSING REFUSE ON UNIT MASS BASIS

Function	$/Mg	Percentage of total
Tipping floor	1.29	6.88
Shredding	2.15	11.46
Air density separation	0.58	3.09
Processed ferrous metals	1.27	6.77
Nonprocessed ferrous metals	0.10	0.53
Nonferrous	0.44	2.35
Control room	0.50	2.67
Log chipper	0.08	0.43
Indirect labor	1.29	6.88
General expenses	0.33	1.76
Indirect electrical energy	0.66	3.52
Water and sewage	0.13	0.69
Landfill	0.09	0.48
Insurance	0.69	3.68
Equipment depreciation	3.70	19.72
Building depreciation	5.46	29.09
Total	18.76	100.00

TABLE 16. TOTAL LABOR ACTIVITY DISTRIBUTION FOR 1977

Activity	Percent
1. Clean process area	20.48
2. End loader	10.19
3. Conveyors	8.13
4. Tipping floor	7.93
5. Control room	7.12
6. Operations and grates	5.79
7. Maintenance	5.20
8. Secretarial and tours	4.69
9. Pneumatic conveying	4.68
10. Nonferrous separator	3.76
11. Rejects hauling	3.60
12. Shredders and hammer changes	3.00
13. Custodial	2.89
14. Air classification system	2.69
15. Paper baler	2.63
16. Landfill	2.58
17. Miscellaneous	1.62
18. Ferrous separation	1.54
19. Wood chips	0.55
Monthly average 2,312.69 hr	

The hours given represent a total of regular plus overtime hours worked. Hours per month during the 2-year period varied between 1,853 and 2,673. Hours per megagram varied from 0.52 to 0.95.

Maintenance labor on the storage and retrieval system averaged 337 hr/month or 0.13 hr/Mg. An average of 2,586 Mg/month was stored and conveyed throughthe system; this mass flow was determined by the difference of the process plant's input and output streams.

The largest labor cost associated with specific process equipment was for pneumatic conveying, at 4.68%. Major processing equipment receiving a large proportion of processed refuse, thereby incurring high and continuing levels of stress, required relatively little labor. For example, the shredders and ADS system required only 3.00 and 2.69%, respectively. The latter required only slightly more than the paper baler, which was idle more than 80% of the time.

An analysis of downtime identifies subsystems contributing the most to the cost of stopping operations. Table 17 is a summary of downtime for the period June 1976 through October 1977. The air density classification system was highest with 41.9% downtime, followed by the shredder system and pneumatic conveying. Together, these three subsystems accounted for 91% of total downtime for the process plant.

TABLE 17. SYSTEM DOWNTIME SUMMARY (1976-OCTOBER 1977)

Subsystem	Downtime hours	% of Total
Tipping floor	11.45	1.9
Shredding	156.12	26.0
Air classification	251.83	41.9
Ferrous separation	42.14	7.0
Pneumatic conveying	139.52	23.2
Total	601.06	100.0

Total time = Process time + downtime
= 1,857.3 + 601.1 = 2,458.4 hr

Fraction of downtime = 0.244 or 24.4%

Atlas Bin for RDF Storage

It is important to note that downtime caused by the Atlas bin was not included in Table 19. When the Atlas bin is inoperable because of repairs to the sweep drives, flight feed conveyors, or pneumatic lines to the power plant, it is necessary to shut down the process plant. On the other hand, the Atlas bin can still operate and feed RDF to the power plant when the solid waste plant is not operating. During 1977, the Atlas bin averaged 38 hr of downtime (6.5% of available hours) per month.

The average operating cost per megagram of refuse stored in the Atlas bin and conveyed from the bin to the power plant was \$3.22/Mg (\$2.92/ton). When capital recovery with 6% interest is included, the total cost is \$8.60/Mg (\$7.81/ ton), based on current estimates ((3), p. 70).

ELECTRICAL ENERGY CONSUMPTION

The distribution of electrical energy among major items of machinery in the process plant is shown in Table 18. The average usage of electrical energy was 52 kWh/Mg of processed refuse. Of special interest is the fact that indirect usage was greater than direct usage among subsystems requiring large motors. When examined in terms of kilowatt-hours per megagram, the comparison is striking. The two shredders, each with a 746-kW (1,000 hp) motor, consumed only 6 and 9 kWh/Mg (5 and 8 kWh/ton), or 11 and 16% of total electrical energy, respectively.

TABLE 18. DISTRIBUTION OF ELECTRICAL ENERGY USED FOR PROCESS PLANT

Area	Percent	kWh/Mg
Shredder 1	11	6
Shredder 2	16	9
ADS Fan	8	4
PSI Blower	6	3
Indirect	59	30
Total	100	52

The indirect category includes all conveyors (16 of the 32 actually operating since the nonferrous metal removal system was not used significantly during the study period), bucket elevators (one of five actually operating for the reasons just given), magnets for ferrous removal, and heating and air-conditioning for the control room, office, conference room, rest rooms, and locker room. The magnitude of the indirect electrical power consumption emphasizes the need for total system analysis in planning. Heating and air-conditioning account for a large portion of indirect power consumption when comparison is made of spring and fall to winter and summer. Improved design of the control and office section of the plant utilizing environmental contributions to heat flow plus improved air circulation in these areas could reduce this cost. Since the power plant is only 335 m (1,100 ft) away, the use of a steam line to replace electrical heating may be feasible. Storage and retrieval energy consumption for the Atlas bin and pneumatic transfer of refuse to the power plant was 12.7 kWh/Mg in 1977.

Figures 13 and 14 show total expenditures for electrical energy, total megagrams processed, and cost per megagram on a monthly basis for 1976 and 1977 at the Ames plant. Tables 19 and 20 show a cost breakdown for 1976 and 1977, respectively, based on demand charge, energy charge, and fuel adjustment charges. A large increase in the cost of electrical energy went into effect in July 1977. This affected the demand charge (based on the maximum 15-min demand in a given month), the energy charge (base cost per kilowatt hour), and the fuel adjustment factor (determined from fuel price fluctuations). In 1977 demand charges increased 36% over 1976, and the total energy charge increased 39%. The energy cost per megagram of raw refuse processed has increased 18% from $1.78 in 1976 to $2.10 in 1977.

REVENUES

Revenues from Reclaimed Materials

In Ames, the combustible light fraction of RDF leaving the ADS system is approximately 84% of total processed refuse based on flow stream differences. Ferrous metals constitute another 6% and nonferrous heavy rejects total 9% (4). Other materials make up an insignificant percentage of the total.

Revenues produced from the sale of recovered materials in 1977 totaled $494,264, or $11.25/Mg of refuse processed. Primary sources of revenue were RDF and metals, which accounted for 71 and 21%, respectively, of total revenues received for materials. Of importance in determining the economy of producing and selling reclaimed materials is the price received for them. The price of ferrous metal fluctuates with market conditions and the import-domestic production balance in the United States.

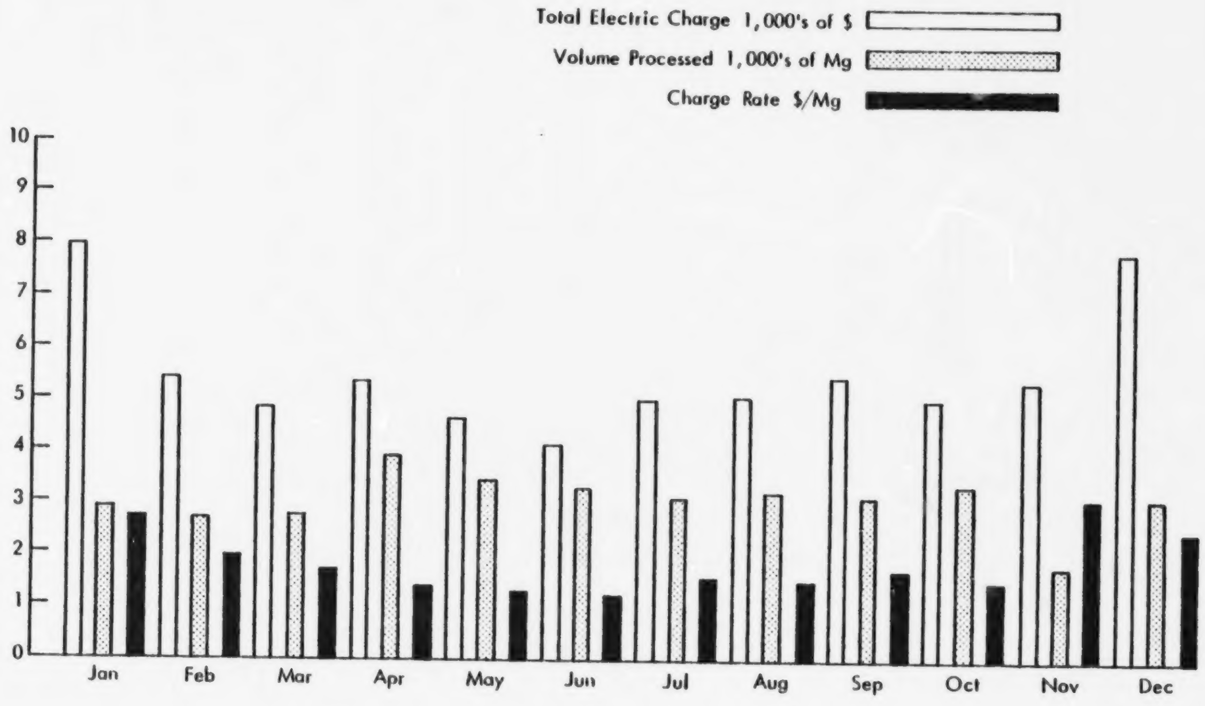

Figure 13. Monthly processing electrical energy costs - 1976.

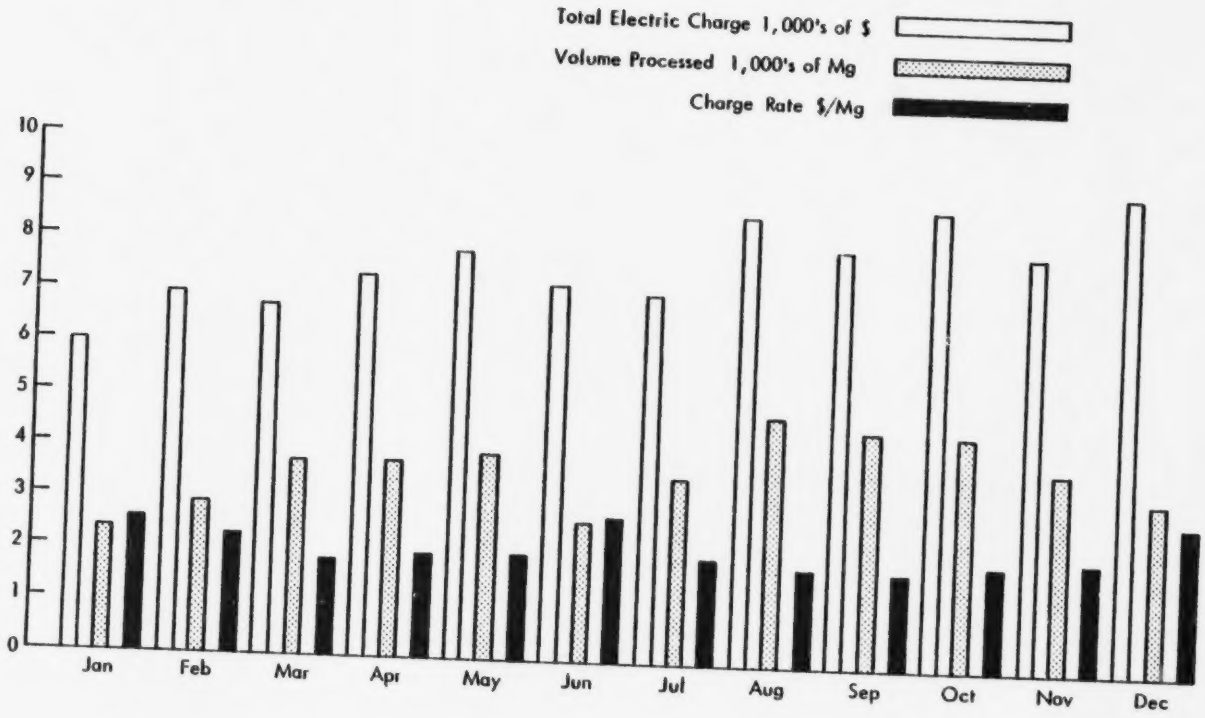

Figure 14. Monthly processing electrical energy costs - 1977.

TABLE 19. AMES SOLID WASTE RECOVERY SYSTEM ELECTRICAL ENERGY CONSUMPTION COST (1976)

Month	Power demand charge ($)	Total consumption charge ($)	Fuel adjustment charge ($)	Total electric bill ($)
January	1,648.44	3,224.04	2,541.79	7,414.27
February	1,605.69	2,738.16	1,363.39	5,421.88
March	1,511.64	2,518.31	1,675.38	5,420.06
April	1,460.34	2,502.11	1,663.31	5,344.47
May	1,343.49	2,281.63	1,244.79	4,626.41
June	1,275.09	2,108.78	1,076.80	4,237.64
July	1,297.89	2,458.48	1,511.27	5,004.26
August	1,426.14	2,444.18	1,447.32	5,051.76
September	1,397.64	2,466.96	1,955.94	5,529.51
October	1,409.04	2,231.64	1,643.14	5,019.63
November	1,420.44	2,293.32	1,956.69	5,386.93
December	1,782.53	3,674.96	2,802.73	7,848.16
Total	17,578.37	30,942.57	20,882.55	66,304.98

Note: Discount (5%) is allowed after all of the charges are totaled.

TABLE 20. AMES SOLID WASTE RECOVERY SYSTEM ELECTRICAL ENERGY CONSUMPTION COST (1977)

Month	Power demand charge ($)	Total consumption charge ($)	Fuel adjustment charge ($)	Total electric bill ($)
January	1,391.94	2,809.86	2,059.80	5,948.30
February	1,738.22	3,258.69	2,289.50	6.922.09
March	1,534.44	3,131.41	2,533.50	6,839.48
April	2,033.19	3,125.79	2,586.77	7,358.44
May	2,155.00	5,482.91	605.11	7,830.87
June	2,361.00	4,711.77	545.30	7,237.17
July	2,043.00	4,902.04	460.68	7,035.43
August	2,061.00	6,176.66	922.21	8,701.88
September	2,501.00	5,325.10	639.20	8,042.03
October	2,051.00	6,273.49	1,006.91	8,864.83
November	1,925.00	5,419.34	1,051.47	7,976.01
December	2,171.00	6,286.54	1,269.58	9,240.76
Total	23,975.29	56,903.60	13,910.23	91,997.29

Note: 5% discount allowed after all charges are totaled.

Monthly quotations are given in several trade journals. The price received during 1976 and 1977 averaged $40.64/Mg ($36.90/ton) and ranged from $34.39 to $46.93/Mg. The average price was derived by combining weighted averages of revenues received for processed and nonprocessed metal. Fluctuations suggest the possibility of storing several months production of ferrous metal for sale at the higher prices.

The price received per megagram of RDF delivered to the power plant has also varied. This variation is primarily due to the fact that there is no direct measurement of the weight of RDF. The plant was designed and constructed without provision for weighing the produced RDF. The megagrams of RDF delivered to the power plant therefore must be estimated by deducting from the weight of raw refuse received, the weight of recovered ferrous metals and the weight of reject material hauled to landfill. This procedure does not account for weight loss due to possible moisture loss during processing, pneumatic conveying and storage and for spillage. The revenue credited to the refuse processing plant for the RDF is based on a calculation of the amount of coal not used that otherwise would have been needed to produce electric power had RDF not been used. Therefore, variability of RDF heating value caused by composition variability results in fluctuations in revenues. The variability in moisture content and spillage results in fluctuations in the estimated amount of RDF produced. It is recommended that future plants producing RDF be designed so that the RDF may be weighed. This would solve many of the problems associated with the Ames plant in determining the revenues to be received for RDF.

Revenues from Customers Delivering Refuse

Customers delivering refuse to the process plant are classified as private customers or credit card customers. Private customers are those without a refuse charge account who do not deliver refuse on a regular basis. They pay a fee of $0.50 per automobile or pickup truck. Those with larger trucks are charged $1.00 per delivery. Customers delivering on a regular basis are issued credit cards and billed monthly at a rate of $1.00 per delivery. The amount of refuse delivered by private customers is less than 10% of the total, but they generate over 47% of the customer delivery tipping fee revenue. Credit card customers provided $13,121 in revenues during 1977, and fees from customers without credit cards totaled $11,843. Revenues received for 1977 from process plant operations, including sales and fees, are summarized in Table 21 (4).

TABLE 21. SUMMARY OF 1977 REVENUES

Source	Revenue ($)	Percent
Refuse-derived fuel	353,325	71.48
Ferrous metals	105,571	21.36
Regular customers fees	13,121	2.65
Public fees	11,843	2.40
Baled paper	7,652	1.55
Wood chips	2,752	0.56
Total	494,264	100.00
Monthly average	41,189	

It is clear that the production and sale of RDF are critical in considering a financial return on recycling operations. The effects of price and production volume of RDF upon the determination of a break-even point are discussed in the following section.

BREAK-EVEN ANALYSIS

A break-even analysis of the solid waste processing plant reveals important information relating the volume of refuse processed per month to the recovery of investment and operating costs. Linear regression equations were computed for total expenses based on city accounting records (not considering capital recovery plus return) as were total actual revenues for the 24-month period, 1976 and 1977. Total monthly expenses and revenues were computed using actual prices and costs. The following equations express total monthly costs and revenues as a function of volume processed per month.

Total Monthly Expense: $\hat{y} = \$1.38\,(X) + \$81{,}004$ (1)

$R^2 = 0.0095$

$\bar{y} = \$85{,}157$

where $\hat{y}$ = Totals monthly expense

X = Tons processed per month

R^2 = Correlation coefficient

$\bar{y}$ = Average monthly expense

Total Monthly Revenue: $\hat{y} = \$6.31\ (X) + \$16{,}003$ (2)

$R^2 = 0.41$

$\overline{y} = \$39{,}473$

where $\hat{y}$ = Totals monthly revenue

X = Tons processed per month

R^2 = Correlation coefficient

$\overline{y}$ = Average monthly revenue

At the break-even point,

$$X = \frac{81{,}004 - 16{,}003}{6.31 - 1.38} = 13{,}185 \text{ tons/month } (11{,}972 \text{ Mg/month})$$

Total monthly expense have a high correlation with total volume processed per month. One reason for this is that many expenses occur sporadically and are not necessarily related to volume processed during a particular month. Another reason is that all bills are charged to the month in which they are paid (an accounting practice) even though the actual expense may have occurred during a previous month. It can be seen in Eq. (1) that a monthly expense of $81,004 exists whether or not any refuse is processed. This fact underscores the capital-intensive nature of solid waste recovery systems and the need to develop effective operating techniques to avoid system downtime. Total monthly expenses averaged $85,157 during the 24-month period.

Equation (2) indicates that $16,003 would be received per month even if no refuse were processed; this is partially due to the tipping fees. The rather low correlation coefficient results largely from variation in prices received for RDF and ferrous metal. Total monthly revenues averaged $39,473.

Based on prevailing costs and prices during the past 2 years, the break-even point appears to be 11,972 Mg (13,185 tons) per month. The average volume of refuse processed per month in 1977 was 3,658 Mg.

As a matter of interest, an investigation was initiated to determine the sensitivity of the break-even point to variations in prices received for RDF and for ferrous metal. During the period 1976-1977, the maximum and minimum fuel credits received were $14.67 and $7.31/Mg ($13.32 and $6.34/ton), respectively. In repeating the break-even analysis, Eq. (1) was used to represent total monthly expense. Actual prices received for ferrous metals were used to represent that portion of revenue. When the maximum fuel price was used to represent all RDF, the following revenue equation resulted:

$$y = \$11.53\,(X) + \$10{,}362 \qquad (3)$$

$$R^2 = 0.91$$

$$\bar{y} = \$53{,}263$$

Equating Eq. (3) with Eq. (1) and solving for X yields:

$$X = \frac{81{,}004 - 10{,}362}{11.53 - 1.38} = 6{,}960 \text{ tons/month or } 6{,}320 \text{ Mg/month}$$

Thus, using the maximum fuel price received to represent prices received throughout the 24-month period resulted in a break-even point equal to a volume 1.72 times the average monthly processing rate for the period. The maximum volume of refuse processed per month during the 2-year period was 4,734 Mg (5,218 tons). Using the maximum fuel price provides a break-even point within the operating capacity of the plant and within the refuse-producing and delivering capacity of the city and other nearby towns. The correlation coefficient was also high in this case.

The analysis was repeated using the minimum price received for RDF as a basis for computing all fuel revenues. Actual ferrous prices were used as before. The equation generated under this assumption is:

$$y = 6.17X + 9{,}343 \qquad (4)$$

$$R^2 = 0.79$$

$$\bar{y} = 32{,}290$$

Equating Eq. (4) with Eq. (1) and solving for X yields:

$$X = \frac{81{,}004 - 9{,}343}{6.17 - 1.38} = 14{,}961 \text{ tons/month or } 13{,}584 \text{ Mg/month}$$

The break-even monthly volume of processed refuse resulting from the use of the minimum price received for RDF is 2.9 times the maximum amount processed per month. The correlation coefficient was moderately high in this case.

It is significant that the break-even point calculated using the minimum price received is within 1,612 Mg (1,775 tons) of the break-even point calculated using the actual price received. It is clearly evident that the break-even point in terms of monthly operating volume is strongly affected by the price received for fuel.

A similar analysis was conducted using maximum and minimum prices received for ferrous metals over the 2-year period. Actual monthly fuel revenues were used to represent the contribution of fuel revenues. During the period 1976 to 1977, the maximum and minimum prices received per ton of ferrous metal were \$46. 93 and \$34.39/Mg (\$42.61 and \$31.23/ton), respectively. Equation (1) was used to represent total cost. Using the maximum price received for ferrous metal, the following equation resulted:

$$y = \$9.02\,(X) + \$7{,}691 \qquad (5)$$

$$R^2 = 0.58$$

$$\bar{y} = \$41{,}276$$

Equating Eqs. (5) and (1) provides a break-even point equal to

$$X = \frac{81{,}004 - 7{,}691}{9.02 - 1.38} = 9{,}596 \text{ tons/month or } 8{,}713 \text{ Mg/month}$$

It can be seen that this is 2,393 Mg/month (2,636 tons) more than the break-even volume calculated under the assumption of a maximum price for fuel. This means that 2,393 Mg more refuse would have to be processed per month to reach a break-even point based on maximum ferrous metal prices that would have to be processed to reach a break-even point based on maximum fuel prices. This fact is not surprising when the relative amounts of fuel and ferrous metal sold are compared.

The analysis based on ferrous metal prices was repeated using the minimum price received during the 2-year period. Actual fuel prices received were again used in the calculation. In this case, the resulting equation was:

$$y = \$8.23\,(X) + \$7{,}856 \qquad (6)$$

$$R^2 = 0.55$$

$$\bar{y} = \$38{,}490$$

Taking Eqs. (6) and (1) and solving for X at the break-even point yields:

$$X = \frac{81{,}004 - 7{,}856}{8.23 - 1.38} = 10{,}679 \text{ tons/month or } 9{,}696 \text{ Mg/month}$$

The effect of ferrous metal prices upon the break-even point is far less significant than the effect of fuel prices. The difference in break-even monthly processing rates resulting from assuming maximum and minimum ferrous metal prices received for the 2-year period is 9,696 minus 8,713, or 983 Mg/month (1,082 tons), a figure within the normal variation experienced over a 2-year period.

Some additional price combinations were used in estimating potential break-even points. Using the highest ferrous and fuel prices to calculate a monthly production break-even point, the following results were obtained:

RDF price = $14.67/Mg (or $13.32/ton)
Ferrous price = $46.93/Mg (or $42.61/ton)
X at break-even point = 6,139 tons/month of 5,574 Mg/month

This presents a slightly more favorable figure than that calculated for maximum fuel price and an average ferrous metal price.

SUMMARY OF TOTAL EXPENSES AND REVENUES

Using data accumulated during 1976 and 1977, the following overall expense and revenue summaries were generated:

	Total expenses by percentage
Principal and Interest	49%
Contractual Expenses	27
Salaries and Wages	16
Supplies and Commodities	8
	100%

Major items associated with contractual expenses include:

- Insurance
- Coal, fuel oil, gas
- Electrical power
- Water (for sewage and tooling)
- Equipment repair and maintenance repair by non-city personnel
- Fixed plant and equipment repair and maintenance
- Rental or equipment
- Interdepartmental equipment rental
- Construction contract payments

Revenue categories are:

	Total expenses by percentage
Fuel revenue	71.0%
Ferrous metal revenue	22.0
Public fees	3.0
Regular customers	3.0
Baled paper	0.6
Wood chips	0.4
	100.0%

An examination of the foregoing break-even analysis and of the relative contribution of major costs and revenues to overall operational economics clearly shows that the major economic challenge of municipal solid waste processing lies in offsetting principal, interest, and contractual expenses (76% of total expenses) with fuel and ferrous revenues (93% of total revenues). The break-even analysis indicated that fuel revenues have the dominant influence on the overall revenue-expense ratio.

ALTERATIONS AND DECISIONS FOR THE FUTURE

Experience in operating the plant over the 2-year study period and in documenting costs and revenues associated with the process and its subsystems has led to the consideration of several major alterations in the processing plant. One of the alterations is the installation of a disc screen separator between the first ferrous removal system (following primary shredding) and secondary shredding. This system is expected to cost $230,000. It will benefit the system in two ways. First, it will remove material small enough that it does not need to be shredded a second time, which will help to reduce power surges and wear on the second shredder. Second, it will remove grit from the refuse and thereby help reduce wear in the pneumatic lines and improve the quality of fuel for the power plant.

A second alteration seen as beneficial is a dust collection system to reduce dust generated by shredding and the ADS. Such a system will substantially reduce the cost of labor to clean the processing area following daily operation. This cost is about 20% of total labor costs. The dust collection system is expected to cost $166,000.

Another alteration which would improve cost and revenue estimating is a weighing system to monitor the mass flow of RDF to the power plant. The importance of fuel price received for RDF in achieving a break-even point in resource recovery economics has already been demonstrated. Measuring the quantity of RDF is also of importance in understanding cost-revenue relationships. The physical nature of this system has not yet been determined. A continuous loop of buckets on a chain conveyor is used to monitor coal consumption. Such a system may also be suitable for monitoring the flow of RDF.

CONCLUSIONS

1. The economics of solid waste recovery depends upon the relationship between major costs (principal and interest plus contractual expenses) and revenues (from RDF, ferrous metal and tipping fees).

2. The most significant cost of the system results from principal and interest associated with the process plant. The most significant revenue for the system results from the sale of fuel to the power plant. The relationship between this cost and revenue is critical in determining a monthly break-even volume of processed refuse.

3. Handling of material can present serious problems in the operation of a solid waste recovery system. Material handling and separation methods must be designed to cope with variability in refuse composition and density. The removal of gritty material and dust from flow streams is desirable from the standpoint of both maintenance and safety.

4. Capital recovery plus return provide a better method of determining operating cost than do traditional depreciation methods used by municipalities.

5. Close cooperation of all municipal employees involved with the operation of a resource recovery plant and with the use of its products is necessary for a successful operation.

SECTION 4

FLOW STREAM CHARACTERIZATION

GENERAL PROCEDURE

Initial flow stream sampling began July 5, 1977, and continued through July 13, 1978, in order to allow for characterization on a monthly and a seasonal basis. Sampling was conducted at 12 locations. Eleven locations were inside the process plant and one on top (inlet) of the Atlas storage bin. These locations are tabulated in Table 22.

Samples were taken by using a container attached to the end of a rod and passing it back and forth in a free-fall flow stream until the container was full. Samples were taken at 1.5 hr intervals beginning approximately 15 min after process plant start-up. Weekly composite samples for each location were generated, and from these, appropriate subsamples were prepared for the various analyses shown in Figure 15 and Table 23.

Weekly composites were developed from samples collected from Friday through the following Thursday. Each day's samples were placed in a 3-mil plastic bag near each sampling location and left there throughout the day. The bags were tied securely and labeled with the date, conveyor number, and daily sample numbers. At the end of the Thursday sampling, the week's samples were taken from the process plant to a mixing lab on the Iowa State University campus in Ames. On Friday each location's accumulated samples were mixed in a 0.2 m^3 (6 ft^3) cement mixer. From the mixer representative samples were removed, as shown in Figure 15. This procedure allowed for prompt shipment of samples from the sampling sites S-1, S-2, S-8, S-9, and S-10 to Raltech Laboratories in St. Louis, Missouri, for appropriate analytical analysis. Mixing on Friday also allowed for pasteurization of all samples at 105°C (221°F) over the weekend before handpick classification was started the following Monday.

Figure 16 is the flow chart of the sampling sequence. The sequence started at the top level, the third floor, and worked down through the second and first floors to the basement. The last sample was taken at the Atlas storage bin. The following is a detailed description of the sampling sequence.

TABLE 22. SCHEDULE OF PROCESSING PLANT FLOW STREAMS TO BE SAMPLED AND CURRENT STATUS

Sample I.D. No.	Description of flow stream	Samples being taken	Reason if samples not being taken
	Plant input/output		
S1	Raw refuse - 1st stage shredder discharge - Conveyor C-2 with Dings magnet de-energized	Yes	
S2	RDF - pneumatic conveying cyclone discharge into storage bin	Yes	
S3a/		No	
S4	Total ferrous metal recovered - Belt Conveyor C-13	Yes	
S5	Aluminum recovered - Bucket Elevator E-5	No	Almag inoperative
S6	Other nonferrous metal recovered - Bucket Elevator E-4	No	Almag inoperative
S7A	Sand and glass - Bucket Elevator E-3	No	Almag inoperative
S7B	Nonferrous metal rejects - Bucket Elevator E-2	No	Almag inoperative
S7C	Magnetic Separator No. 4 discharge - metal chute from MAG. Hd. Conveyor C-14	Yesb/	
	Internal flow streams		
S8	Second stage shredder feed - Conveyor C-2 with Dings magnet energized	Yes	
S9	Second stage shredder discharge (feed to ADS) - Belt Conveyor C-6	Yes	
S10	ADS separation chute discharge (ADS heavies) - Belt Conveyor C-7	Yes	
S11	Reject discharge to bin - Belt Conveyor C-15	Yes	
S12	Magnetic Separator No. 1 discharge - Belt Conveyor C-10	No	Inaccessible (Replaced by S-16)

(continued)

TABLE 11. (concluded)

Sample I.D. No.	Description of flow stream	Samples being taken	Reason if samples not being taken
S13	Magnetic Separator No. 2 discharge - Belt Conveyor C-7A	Yes	
S14	Magnetic Separator No. 3 discharge - Belt Conveyor G-12	Yes	
S15	Magnetic Separator No. 4 feed - Bucket Elevator E-1	Yes	
S16	New sampling location at G-11 to replace S-12	Yes	

a/ Sample S3 is RDF discharged from the storage bin that was sampled during Work Task 5. Sample is normally taken during boiler tests.

b/ Called "chute."

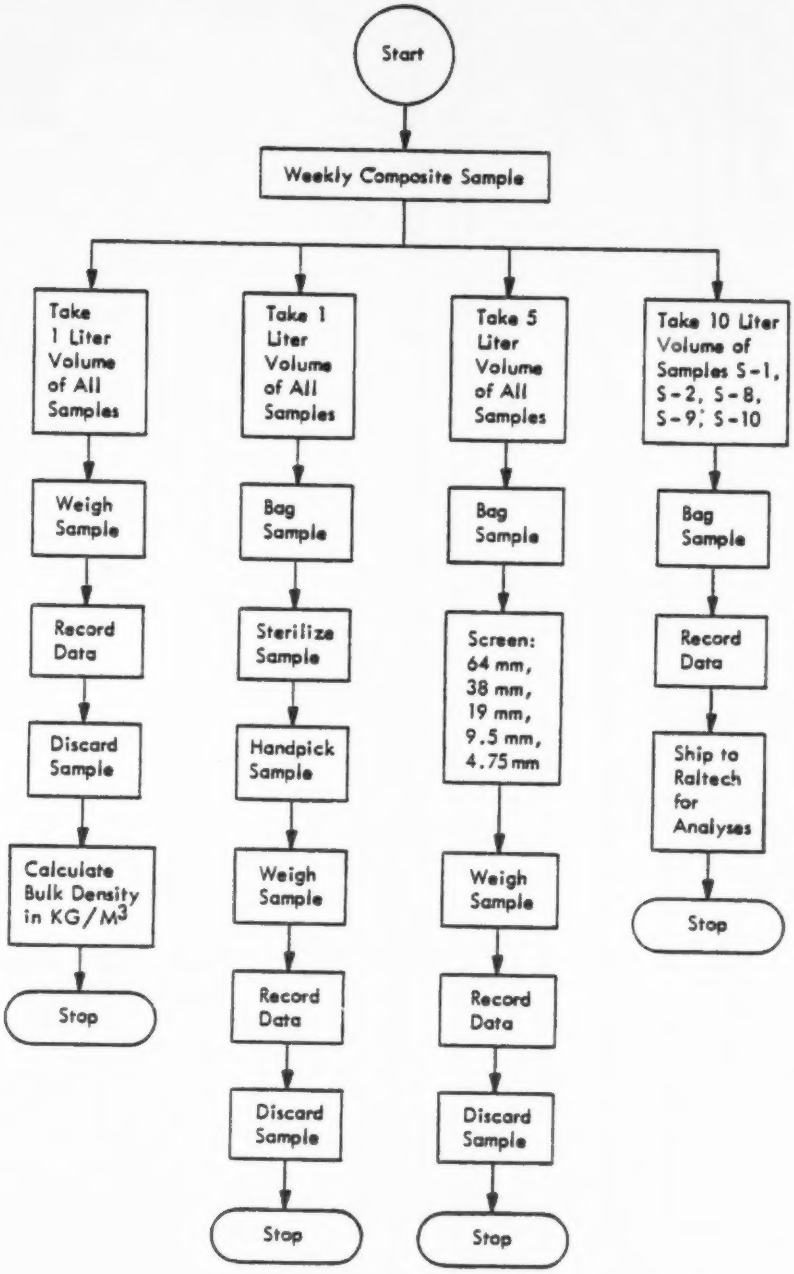
Start
Weekly Composite Sample
Take 1 Liter Volume of All Samples
Weigh Sample
Record Data
Discard Sample
Calculate Bulk Density in KG/M3
Stop
Take 1 Liter Volume of All Samples
Bag Sample
Sterilize Sample
Handpick Sample
Weigh Sample
Record Data
Discard Sample
Stop
Take 5 Liter Volume of All Samples
Bag Sample
Screen: 64 mm, 38 mm, 19 mm, 9.5 mm, 4.75 mm
Weigh Sample
Record Data
Discard Sample
Stop
Take 10 Liter Volume of Samples S-1, S-2, S-8, S-9, S-10
Bag Sample
Record Data
Ship to Raltech for Analyses
Stop

Figure 15. Flow chart - laboratory preparation of collected samples.

TABLE 13. ANALYSES PERFORMED ON PROCESS PLANT SAMPLES[a]

Weekly composite sample		Heating value, moisture, and ash	Metals by chemical analysis[b]	Fixed carbon and volatile	Carbon, hydrogen, nitrogen, oxygen, and sulfur
I.D. No.	Description				
S-1	Primary shredder discharge (C-2)	x	x		
S-2	RDF - inlet into Atlas storage bin	x	x	x	x
S-4	Ferrous metal - C-13				
S-7C	Magnetic Separator No. 4 - C-14				
S-8	Second stage shredder inlet feed - C-3 Dings on C-6	x	x		
S-9	Second stage shredder discharge	x	x		
S-10	ADS heavy discharge - C-7	x	x		
S-11	Heavies discharge C-15				
S-13	Magnetic Separator No. 2 - C-7A				
S-14	Magnetic Separator No. 3 - C-12				
S-15	Magnetic Separator No. 4 feed - Bucket Elevator E-1 discharge				
S-16	Magnetic Separator No. 3 return - C-11				

a/ All streams: Screening sized for 64, 38, 19, 9, 4, 2 mm
Handpick Classifications:
1. Cardboard
2. Other paper
3. Plastic
4. Wood
5. Glass
6. Ferrous metal
7. Nonferrous metal
8. Natural, organic
9. Cloth
10. Tar
11. Misc. (sand, grit, rock, dust)

b/ Metals analyzed for aluminum, copper, iron, lead, nickel, and zinc.

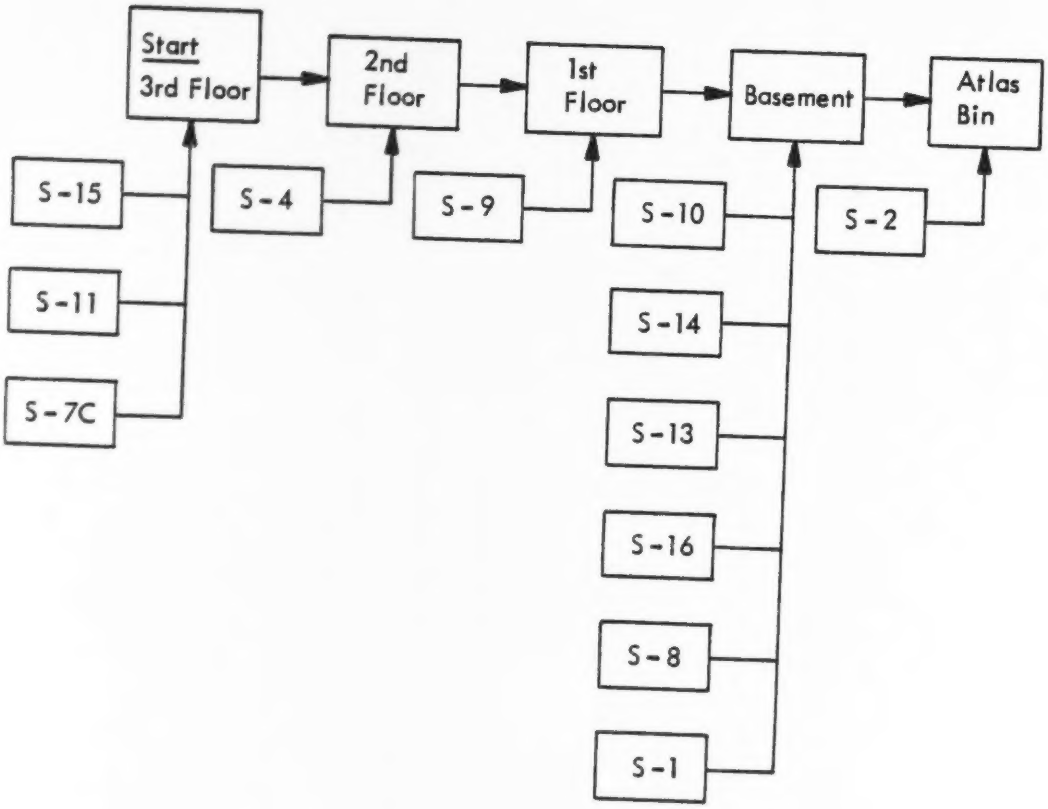
Start
3rd Floor
2nd Floor
1st Floor
Basement
Atlas Bin
S-15
S-11
S-7C
S-4
S-9
S-10
S-14
S-13
S-16
S-8
S-1
S-2

Figure 16. Processing plant sampling sequence flow chart.

Third Floor

1. Sample No. S-15 is magnetic separator No. 4 feed and is taken from bucket elevator E-1.

2. Sample No. S-11 is nonferrous metal separation system feed to the noncombustible bin and is taken from conveyor C-15.

3. Sample No. S-7C is magnetic separator No. 4 discharge belt conveyor C-15 and is taken from the metal chute at the magnetic head pulley where C-14 dumps onto C-15.

Second Floor

4. Sample No. S-4 is ferrous material recovered at belt conveyor C-13.

First Floor

5. Sample No. S-9 is second stage shredder discharge (feed to the ADS system) and is taken at conveyor C-6.

Basement

6. Sample No. S-10 is ADS separation chute discharge (ADS heavies) and is taken at conveyor C-7. To make this sample, the C-7 conveyor belt must be reversed, so a reversing switch was installed to permit sampling at an accessible location by reversing the direction of the belt.

7. Sample No. S-14 is magnetic separator No. 3 discharge taken at belt conveyor C-12.

8. Sample No. S-13 is magnetic separator No. 2 discharge taken at belt conveyor C-7A.

9. Sample No. S-16 is magnetic separator No. 1 discharge taken at belt conveyor C-11.

10. Sample No. S-8 is second stage shredder feed taken at the discharge of conveyor C-2 with the Dings magnet operating.

11. Sample No. S-1 is raw refuse taken at first stage shredder discharge. To make this sample, the Dings magnet must be turned off for about 15 sec.

12. Sample No. S-2 is the RDF produced and is sampled at the inlet to the Atlas storage bin in the coal yard between the processing plant and the power plant.

At the end of each week, the accumulated daily samples were composited in a 0.2 m^3 (6 ft^3) cement mixer. Three samples were taken from each composited sample; and a fourth sample from each of the following: S-1, S-2, S-8, S-9, and S-10. Figure 17 shows the volume of sample taken from each composite and its dispensation.

The following is a list of the university laboratory's activities for a 1-week period.The laboratory week ran from Friday morning to Thursday evening.

Friday: Mix, weigh and screen. Deliver Ames samples to university power plant by 2:30 p.m. for shipment. Place samples in oven to be handpicked on Monday.

Monday: Handpick,* weigh, and record data.

Tuesday: Handpick,* weigh, and record data.

Wednesday: Complete handpicking and recording data. Perform calculations such as bulk density, samples' net weight, percentages, etc., and log all information. Reserve truck for Thursday afternoon to pick up samples from process plant.

Thursday: Clean up lab and prepare for incoming samples. Make ready all necessary supplies. Pick up samples from process plant.

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* Handpick categories include:

(a) cardboard
(b) other paper
(c) plastic
(d) wood
(e) glass
(f) ferrous metal
(g) nonferrous metal
(h) natural organics
(i) miscellaneous (material too small to be visually identified)
(j) other (material that can be identified but does not regularly appear in samples; examples are tar and cloth)

SECTION 5

PERFORMANCE OF THE STOKER-FIRED STEAM GENERATORS

HISTORICAL NARRATIVE

The conceptual design of the solid waste recovery system specified burning RDF in suspension in the pulverized coal-fired unit 7 (33 MW) at a firing rate of 20% (by heat input) or about 7.26 Mg/hr. Initial operation in fall 1975 resulted in a high dropout of unburned material into the bottom ash hopper. The power plant then began burning RDF in the stoker-fired boilers until a solution could be developed. The final solution was the installation of a dump grate at the furnace bottom; this modification, which was completed on April 26, 1978, allowed for the successful burning of RDF in unit 7. It was concluded that a dump grate configuration is also necessary in small- to moderate-sized suspension-fired steam generators. This report covers the period through 1977 and therefore this section discusses only the investigation of the performance of the spreader type stoker-fired steam generators units 5 and 6.

Stoker units 5 and 6 were originally scheduled to burn RDF only when unit 7 was scheduled for maintenance. Thus, because of unit availability, the major research emphasis was on the thermal and environmental evaluation of the stoker-fired units during 1976 and 1977. In 1976, only Iowa coal was burned in unit 5, while a 50 to 50% mixture of Iowa-Wyoming coal was burned in unit 6. In 1976, unit 5 experienced severe fouling at the inlet to the superheater region just above the slag screen. After shutdown and cleaning, the remaining tests were completed. A policy was then instituted of periodic shutdown and cleaning of both units on a 2- to 3-month cycle. Unit 5 was tested at 80% steam load again in 1977 in order to see the impact of Iowa-Wyoming coal burning on emissions. It should be noted that unit 5 was tested at 100% of rated steam load in 1976. However, when firing RDF at 20% and 50% of rated heat input, the insufficient induced-draft fan capacity did not allow for proper burning with sufficient combustion air; in fact, one test run was aborted because the steam flow conditions could not be maintained.

SYSTEM DESCRIPTION

Unit 5 is a Riley RP steam generator with a Riley overthrow spreader and traveling grate. An elevation cross-section view is shown in Figure 17. Unit 6 is a Union Iron Works steam generator with a Hoffman underthrow spreader and continuous return traveling grate. An elevation cross-section is shown in Figure 18. The steam generator characteristics are shown in Table 24.

The RDF is pneumatically conveyed from the Atlas storage bin through two 31.5 cm transport lines and is blown into the furnace approximately 3.4 m above the grate. Two rows of nozzles in the rear furnace wall and two rows of nozzles in the front wall supply overfire air for turbulent mixing of the furnace gases. The total air introduced into the furnace above the grates is 112.1 m^3/min from RDF injection and approximately 106 m^3/min from the overfire air fan. Figure 19 shows the overfire air and RDF injection system arrangement for unit 5.

Both units have dry pneumatic vacuum grate ash hopper and mechanical collector hopper ash removal systems.

TEST PROGRAM

Initial program objectives were to test boilers 5 and 6 at 60%, 80%, and 100% of rated steam load and at RDF firing rates (based on heat energy input) of 0%, 20%, and 50%. Three tests were made at each condition. All tests on unit 5 were completed in 1976 except at the 100% load and 50% RDF, where only two runs were achieved. The experience gained from firing unit 5 at 100% load with RDF was that this firing was not practical. For unit 6, nine tests were performed at 80% load.

In 1976, unit 5 was tested with Iowa coal (high ash and sulfur content), while unit 6 was tested with a nominal 50 to 50% mixture of Iowa-Wyoming coal and varying percentage of RDF heat input. In 1977, unit 5 was again tested at 80% steam load using an Iowa-Wyoming coal mixture with varying RDF flow rates. Nine tests were completed. A complete set of tests on unit 6 at 60% steam load was completed using Iowa-Wyoming coal. Because of the high rate of particulate emissions, an additional set of four tests (two at 0% RDF and two at 50% RDF) were compiled at 80% steam load on unit 6 using sized Iowa coal. Table 25 lists the average properties of the coal and RDF used in the tests.

Test Procedure

The average elapsed test period was 4 to 5 hr once the unit had reached equilibrium. A block diagram showing all sample locations and type of samples collected is shown in Figure 20. Except for several back-to-back tests conducted on the same day, grate ash and mechanical collector ash accumulation rates were measured by truck-weighing of material from the ash silo.

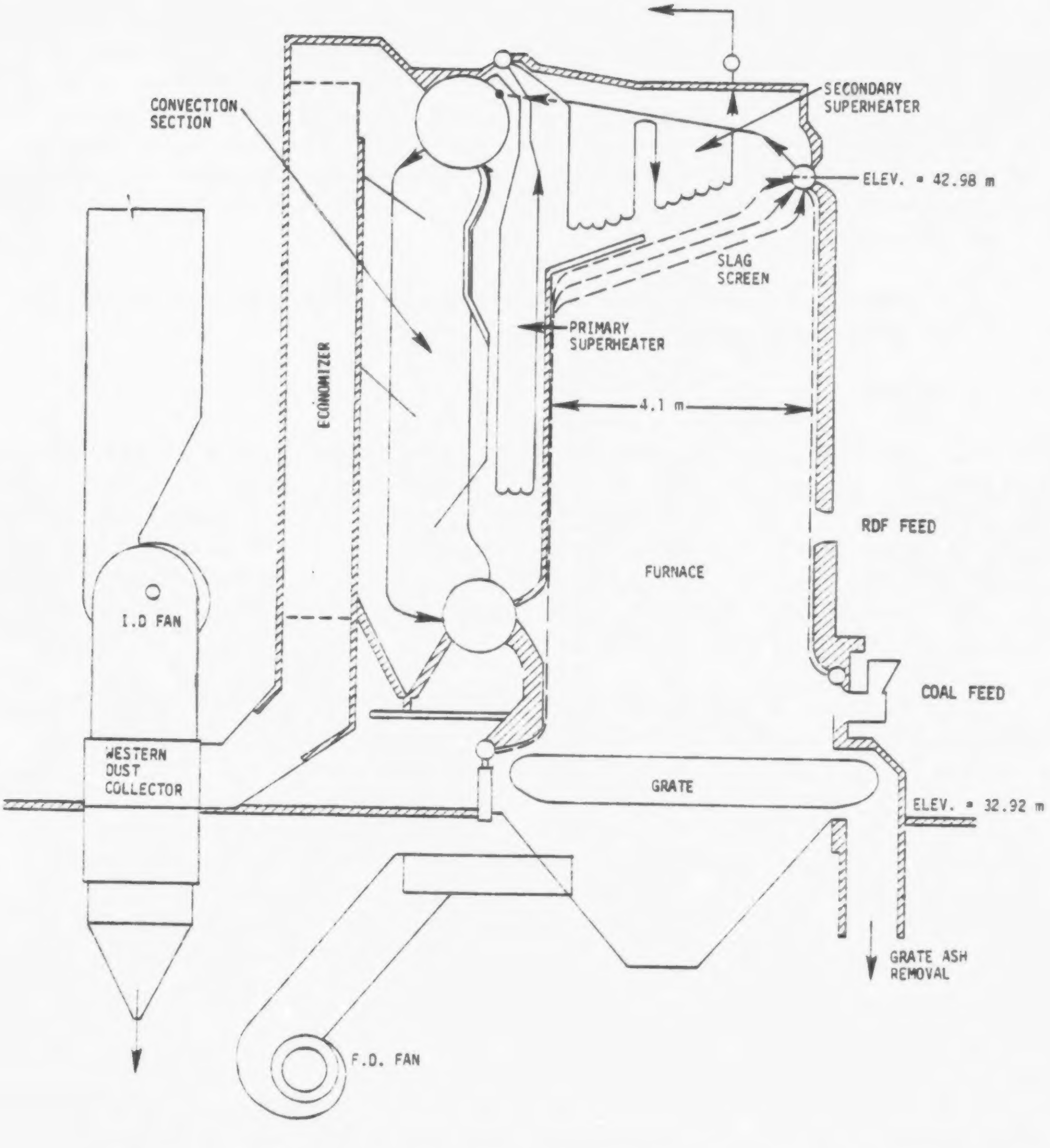
CONVECTION SECTION
SECONDARY SUPERHEATER
ELEV. = 42.98 m
SLAG SCREEN
PRIMARY SUPERHEATER
ECONOMIZER
4.1 m
RDF FEED
FURNACE
I.D FAN
COAL FEED
WESTERN DUST COLLECTOR
GRATE
ELEV. = 32.92 m
GRATE ASH REMOVAL
F.D. FAN

Figure 17. Elevation cross-section of boiler unit 5.

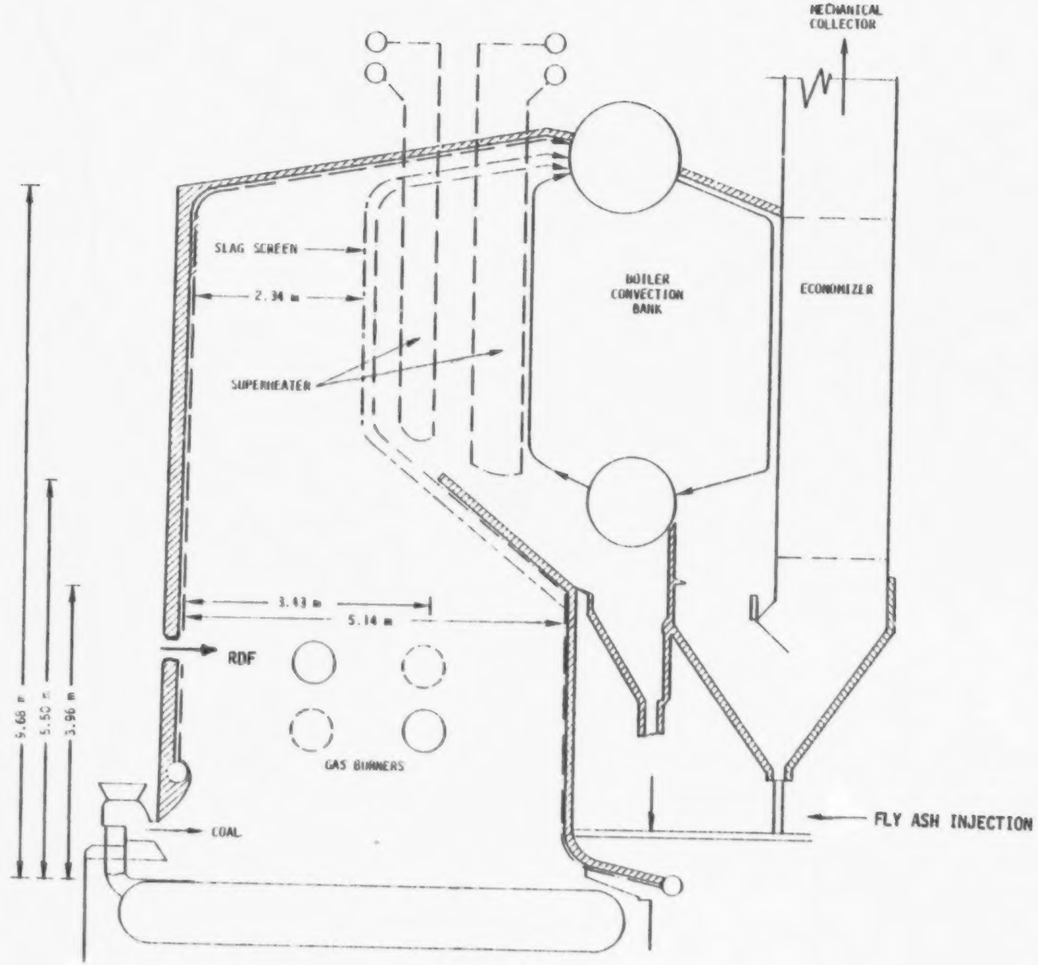
MECHANICAL COLLECTOR
SLAG SCREEN
2.34 m
BOILER CONVECTION BANK
ECONOMIZER
SUPERHEATER
3.43 m
5.14 m
RDF
9.68 m
5.50 m
3.96 m
GAS BURNERS
COAL
FLY ASH INJECTION

Figure 18. Elevation cross-section of boiler unit 6.

TABLE 14. CHARACTERISTICS OF AMES MUNICIPAL POWER PLANT STOKER-FIRED STEAM GENERATORS

Item	Unit No.	
	5	6
Manufacturer	Riley	Union Iron Works
Electrical output, MW	7.5	12
Installation date	1951	1958
Pressure temperature, kpa/°C (psi/°F)	4895/441 (710/825)	4999/441 (725/825)
Nominal steam output capacity, kg/hr (lb/hr)	43,100 (95,000)	56,700 (125,000)
Coal firing equipment	Spreader Stoker Traveling Grate	Spreader Stoker Traveling Grate
Furnace pressure	Balanced Draft	Balanced Draft
Dust collection equipment	Western Multiple Cyclone	American Blower Multiple Cyclone
Stack height, m (feet)	61 (200)	61 (200)
Heat input at nominal capacity, GJ/h (Btu × 10^6/h)	154 (146)	202 (191)

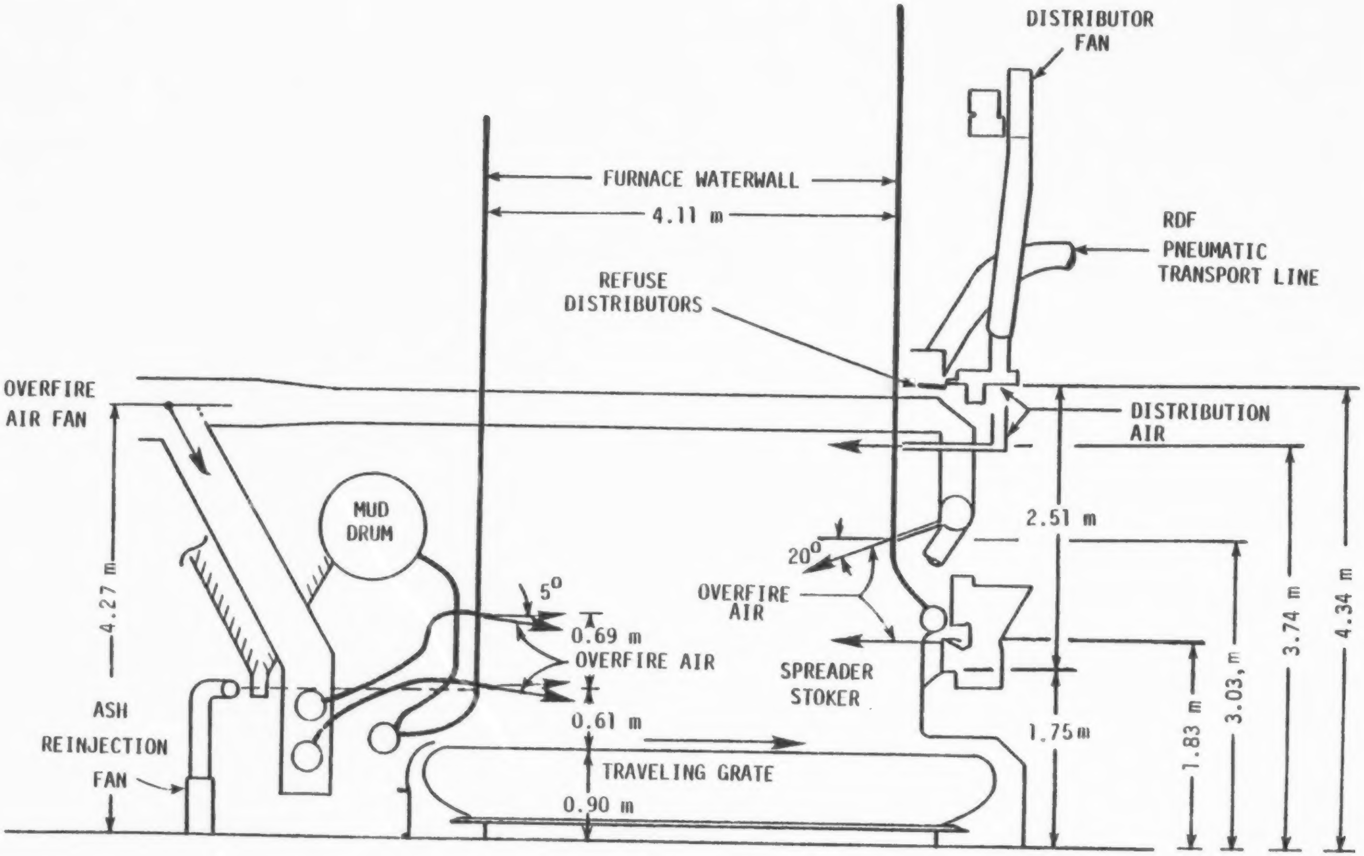
DISTRIBUTOR FAN
FURNACE WATERWALL
4.11 m
RDF
PNEUMATIC TRANSPORT LINE
REFUSE DISTRIBUTORS
OVERFIRE AIR FAN
DISTRIBUTION AIR
MUD DRUM
2.51 m
20°
5°
OVERFIRE AIR
4.27 m
0.69 m
OVERFIRE AIR
SPREADER STOKER
3.74 m
4.34 m
3.03 m
1.83 m
1.75 m
ASH REINJECTION FAN
0.61 m
TRAVELING GRATE
0.90 m

Figure 19. Modified traveling grate of stoker-fired boiler unit 5.

TABLE 25. ULTIMATE ANALYSIS OF FUEL (AVERAGE VALUES)[b]

Year	Load/RDF[a]	Heating value (kJ/kg)		Moisture[a]		Ash[a]		Carbon[a]		Hydrogen[a]		Oxygen[a]		Sulfur[a]		Chlorine[a]	
		Coal	RDF	Coal	RDF	Coal	RDF	Coal	RDF	Coal	RDF	Coal	RDF	Coal	RDF	Coal	RDF
Unit 5																	
1976	60/0	21,000	---	13.7	---	19.7	---	49.4	---	3.38	---	6.88	---	6.91	---	0.06	---
	60/20	20,925	13,700	14.3	21.0	19.7	13.6	49.7	30.6	3.40	2.00	6.34	32.30	6.64	0.35	0.05	0.21
	60/50	21,600	13,633	11.4	21.8	19.5	16.5	52.1	31.6	3.75	2.32	7.58	27.40	5.62	0.22	0.05	0.20
1976	80/0	21.067	---	14.1	---	19.3	---	49.7	---	3.23	---	7.64	---	6.02	---	0.05	---
	80/20	21,467	13,233	14.0	20.4	19.4	17.0	50.3	30.2	3.95	2.36	5.84	29.40	6.64	0.39	0.00	0.22
	80/50	21,133	13,200	14.1	21.6	19.4	17.0	49.4	29.9	3.31	2.24	7.05	28.60	6.72	0.37	0.04	0.37
1977	80/0	22,357	---	16.77	---	11.3	---	55.14	---	3.38	---	1.03	---	3.00	---	0.05	---
	80/20	22,130	14,931	16.92	14.04	12.5	14.16	54.93	34.23	2.96	4.74	9.73	32.06	2.95	0.04	0.04	0.31
	80/50	21,750	13,928	16.97	16.26	13.7	13.71	53.19	33.33	3.29	4.69	9.51	31.20	3.34	0.51	0.06	0.31
1976	100/0	21,100	---	13.2	---	20.3	---	50.6	---	3.52	---	6.07	---	6.25	---	0.07	---
	100/20	21,333	12,433	13.0	21.2	19.1	18.8	51.2	32.7	3.53	2.72	6.63	24.00	6.41	0.51	0.06	0.22
	100/50	21,150	11,400	13.7	26.4	20.1	18.1	50.4	28.4	3.55	2.02	5.93	24.00	6.40	0.67	0.07	0.42
Unit 6																	
1977	60/0	22,258	---	16.68	---	11.35	---	54.91	---	3.14	---	1.08	---	3.01	---	0.07	---
	60/20	22,130	13,707	18.99	15.32	9.72	13.60	54.90	32.4	2.82	4.57	1.11	33.34	2.40	0.43	0.05	0.33
	60/50	21,933	13,717	16.88	16.42	12.00	12.95	54.30	33.98	2.96	4.76	1.06	31.25	3.20	0.39	0.07	0.26
1976	80/0	21,467	---	18.3	---	11.4	---	52.1	---	4.02	---	1.06	---	3.55	---	0.05	---
	80/20	21,500	13,000	18.3	22.2	11.6	15.1	52.2	30.9	3.41	1.88	1.11	29.40	3.34	0.33	0.04	0.24
	80/50	21,833	12,100	17.9	28.3	11.1	14.8	53.0	28.2	3.67	1.12	1.10	26.90	3.19	0.28	0.05	0.37
1977	80/0	22,265	---	16.08	---	10.99	---	55.60	---	2.83	---	1.24	---	2.04	---	0.08	---
	80/50	21,320	14,538	16.63	12.66	14.70	12.8	52.45	34.4	2.57	4.79	1.09	34.61	2.73	0.39	0.04	0.36

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[a] All values in %.

[b] Laboratory analysis of a small number of samples indicated negligible amounts of nitrogen; assumed zero.

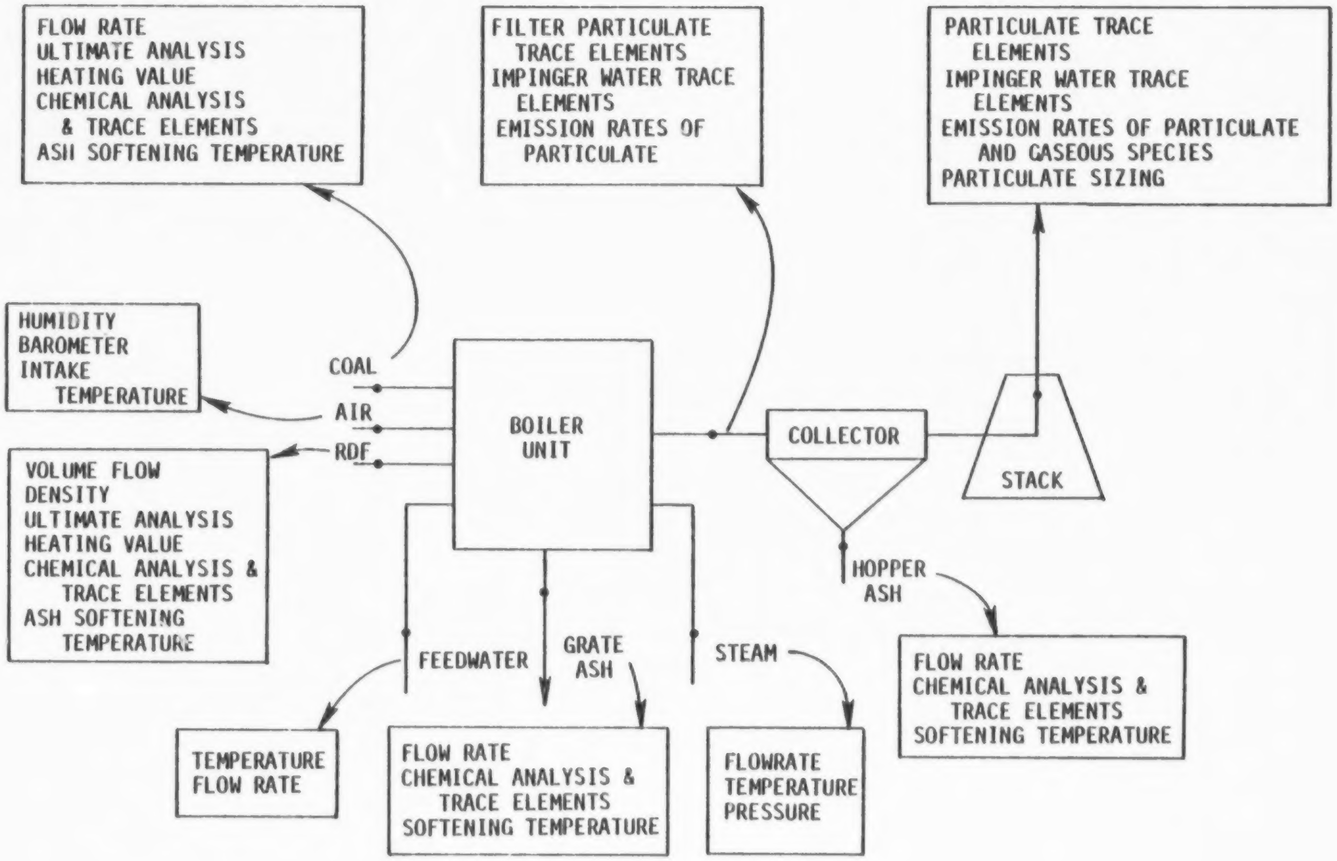
FLOW RATE
ULTIMATE ANALYSIS
HEATING VALUE
CHEMICAL ANALYSIS
& TRACE ELEMENTS
ASH SOFTENING TEMPERATURE
FILTER PARTICULATE
TRACE ELEMENTS
IMPINGER WATER TRACE
ELEMENTS
EMISSION RATES OF
PARTICULATE
PARTICULATE TRACE
ELEMENTS
IMPINGER WATER TRACE
ELEMENTS
EMISSION RATES OF PARTICULATE
AND GASEOUS SPECIES
PARTICULATE SIZING
HUMIDITY
BAROMETER
INTAKE
TEMPERATURE
COAL
AIR
RDF
BOILER
UNIT
COLLECTOR
STACK
VOLUME FLOW
DENSITY
ULTIMATE ANALYSIS
HEATING VALUE
CHEMICAL ANALYSIS &
TRACE ELEMENTS
ASH SOFTENING
TEMPERATURE
HOPPER
ASH
FEEDWATER
GRATE
ASH
STEAM
FLOW RATE
CHEMICAL ANALYSIS &
TRACE ELEMENTS
SOFTENING TEMPERATURE
TEMPERATURE
FLOW RATE
FLOW RATE
CHEMICAL ANALYSIS &
TRACE ELEMENTS
SOFTENING TEMPERATURE
FLOWRATE
TEMPERATURE
PRESSURE

Figure 20. Sample locations and items sampled.

BOILER PERFORMANCE RESULTS

Excess Air

Figures 21 and 22 show the excess air supplied for units 5 and 6 as a function of the percentage of RDF heat input. The firing of the two stoker boilers was controlled manually by the operator until the operator was satisfied with the appearance of the grate bed and furnace. The flue gas was sampled and operators were informed of the carbon dioxide content, which then was held constant for the test. It should be noted that the two RDF transport lines supplied 1.67 m^3/sec of air, while the unit 5 overfire air fan was capable of supplying 1.59 m^3/sec and the unit 6 overfire air fan was capable of providing 2.60 m^3/sec of air. The firing procedure resulted in using all overfire air while burning RDF with coal and in using the lower rows of overfire nozzles on coal only. At 80% steam loads on both units, the induced draft fan control was wide open, which substantiates the presence of high excess air. The effect of higher exit flue gas temperatures while burning RDF also increased the volume flow rate (m^3/sec) handled by the induced draft fan while firing RDF. At the 100% steam load tests on unit 5, the inability of the induced draft fan to maintain negative draft in the furnace limited the amount of combustion air that could be supplied under the grate. This was evident during the tests when the furnace draft pressure would periodically become positive and the operator would have to reduce the air supplied by the forced draft fan.

Excess air supplied during the 1977 tests on units 5 and 6 was less than that for 1976. The average increase in excess air (for all loads on unit 5) in 1976 was 17% for 20% RDF and 34% for 50% RDF as compared to coal alone (0% RDF). The 1977 tests on unit 5 at 80% load (with Iowa-Wyoming coal) resulted in an increase of excess air of 21% for 20% RDF and 14% for 50% RDF as compared to coal alone. The average increase in excess air for unit 6 (for all tests) was 34% for 20% RDF and 37% for 50% RDF compared to coal alone.

Figure 21 indicates that the amount of excess air for unit 5 decreases as percentage steam load is increased. The excess air ranged from an average of 158% at 60% load, 120% at 80% load, to 88% at nominal boiler rating. Figure 22 also shows that the amount of excess air for unit 6 decreases as the percentage steam load increased. The average excess air ranged from 149% at 60% steam load to 115% (1976), to 104% (1977) at 80% steam load.

High excess air flow rates were experienced on both units at all steam load tests while firing coal and coal plus RDF. The boiler operator would reduce both the overfire air and the forced draft fan air as much as possible without having any smoke emissions from the stack. The coal quality was considered poor based on the large number of visible fines present.

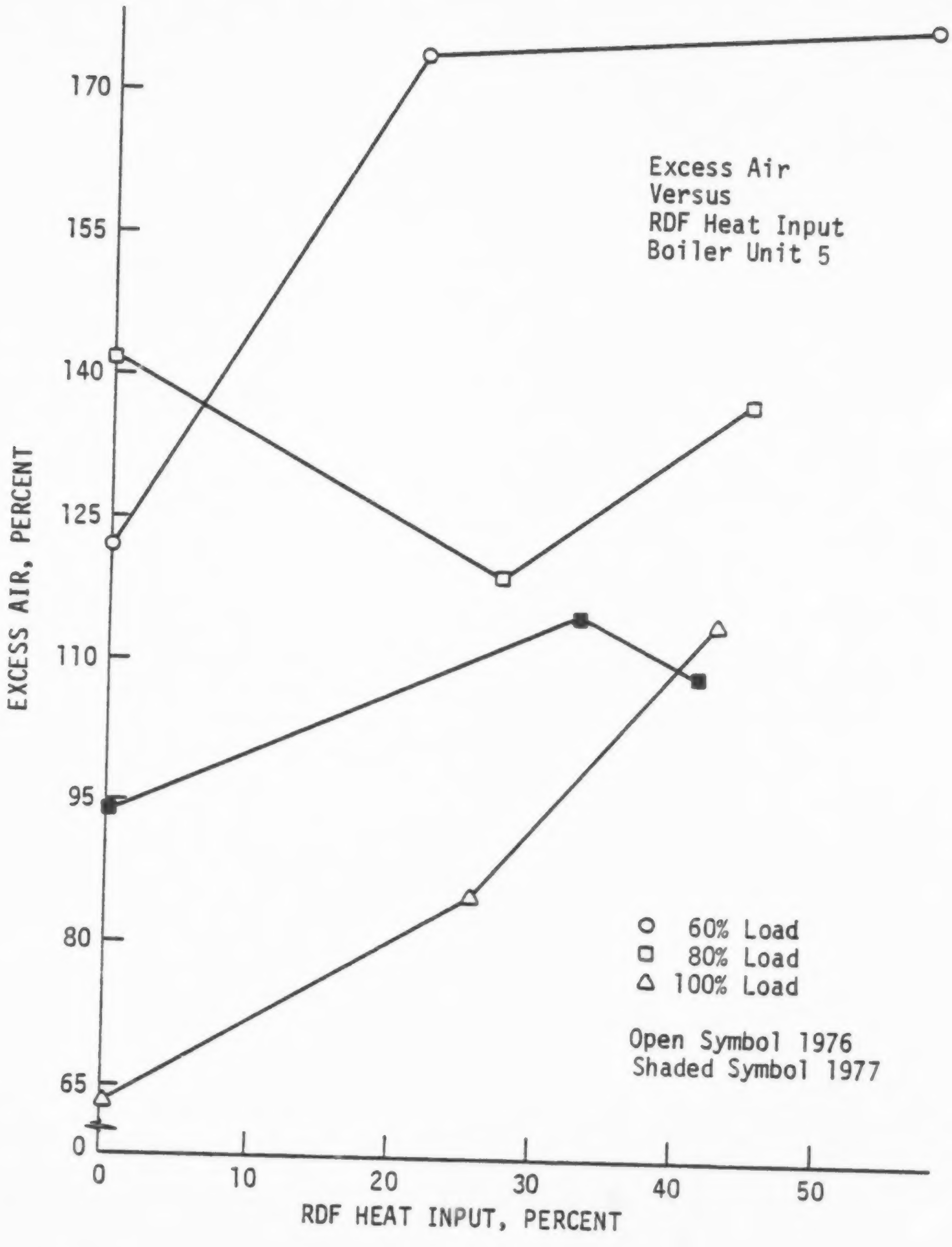

Figure 21. Excess air of boiler unit 5 as a function of RDF heat input.

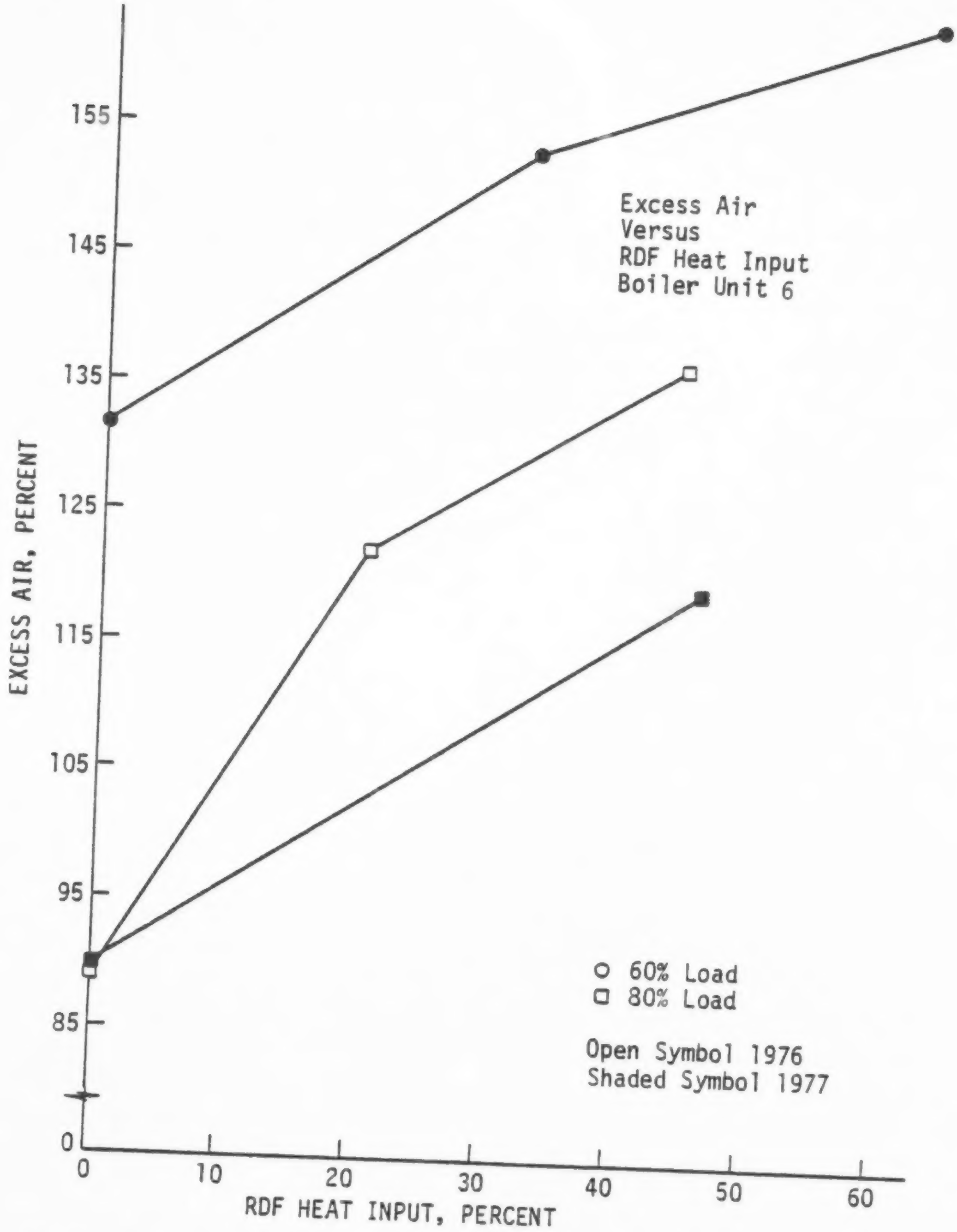

Figure 11. Excess air of boiler unit 6 as a function of RDF heat input.

Boiler Efficiency

The boiler efficiency of both stoker units was determined by the indirect method, which is defined as

$$\eta \text{ indirect} = \left[1 - \frac{Q_{loss}}{\text{heat input}} \right] \times 100\%$$

where

$$Q_{loss} = Q_{loss} \text{ (dry flue gas)} + Q_{loss} \text{ (combustible in ash)}$$
$$+ Q_{loss} \text{ (moisture in flue gas)} + Q_{loss} \text{ (radiation).*}$$
$$+ Q_{loss} \text{ (combustible in flue gas)**}$$

* Extrapolated from ASME Performance Test Code.
** Negligible.

Figures 23 and 24 show the indirect efficiency for units 5 and 6, respectively, for varying percentage RDF heat input. In general, any increase in excess air will increase the dry flue gas heat loss by increasing both the gas flow rate and the exit gas temperature. The moisture heat loss increased when burning RDF due to the presence of higher moisture in the RDF. The heat loss due to unburned combustible in the ash (on an ash per kilogram basis) generally decreased; this behavior is discussed in the subsection below on fuel utilization.

The indirect boiler efficiency, in general, decreased as the percentage RDF heat input increased. For unit 5, the tests at 20% RDF for 60% and 80% steam load resulted in boiler efficiencies that were one to two percentage points lower than tests with 50% RDF. This behavior may be explained by examination of the flue gas exit temperatures listed in Table 28. The excess air increased for those two test loads. However, the gas exit temperatures are higher at the 20% RDF heat input firing rate than those for the 50% RDF input rate, and gas exit temperatures will also increase as a result of reduced heat transfer if slagging of the furnace walls occurs. Thus, excess air supplied might be less at one test condition, but the slagging effect will produce a higher exit temperature. Some of the aforementioned tests during 1976 were performed before the boiler had plugged up and was cleaned on August 3, 1976, and some tests were conducted after this date.

Boiler efficiencies were higher for unit 6 than unit 5. The average boiler efficiency for unit 5 (for all steam loads) decreased from 77.23% at 0% RDF to 74.58 at 50% RDF heat input. The average boiler efficiency for unit 6 (for all steam loads) decreased from 81.30% at 0% RDF (or coal only) to 77.47% at 50% RDF heat input.

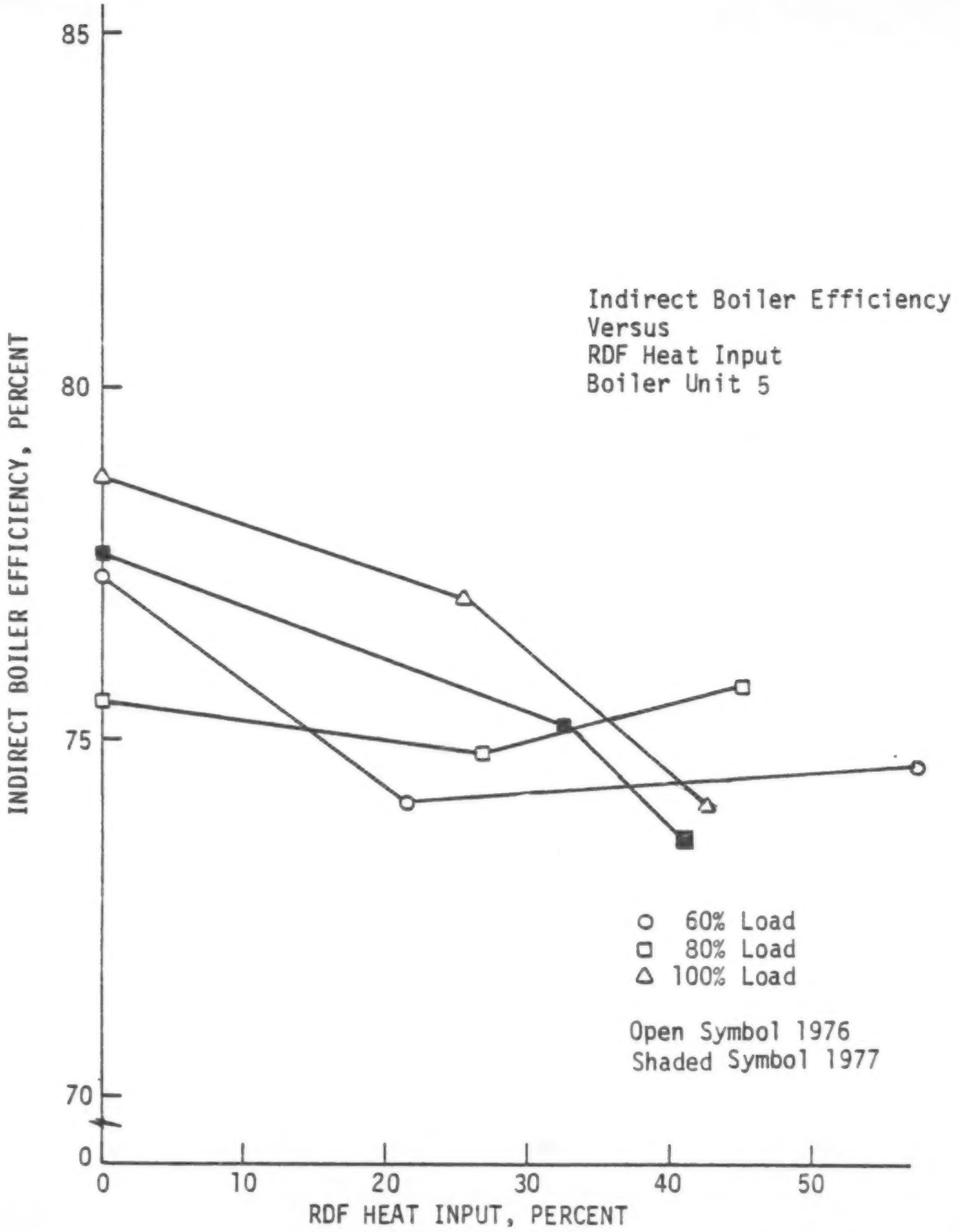

Figure 13. Indirect boiler efficiency of boiler unit 5 as a function of RDF heat input.

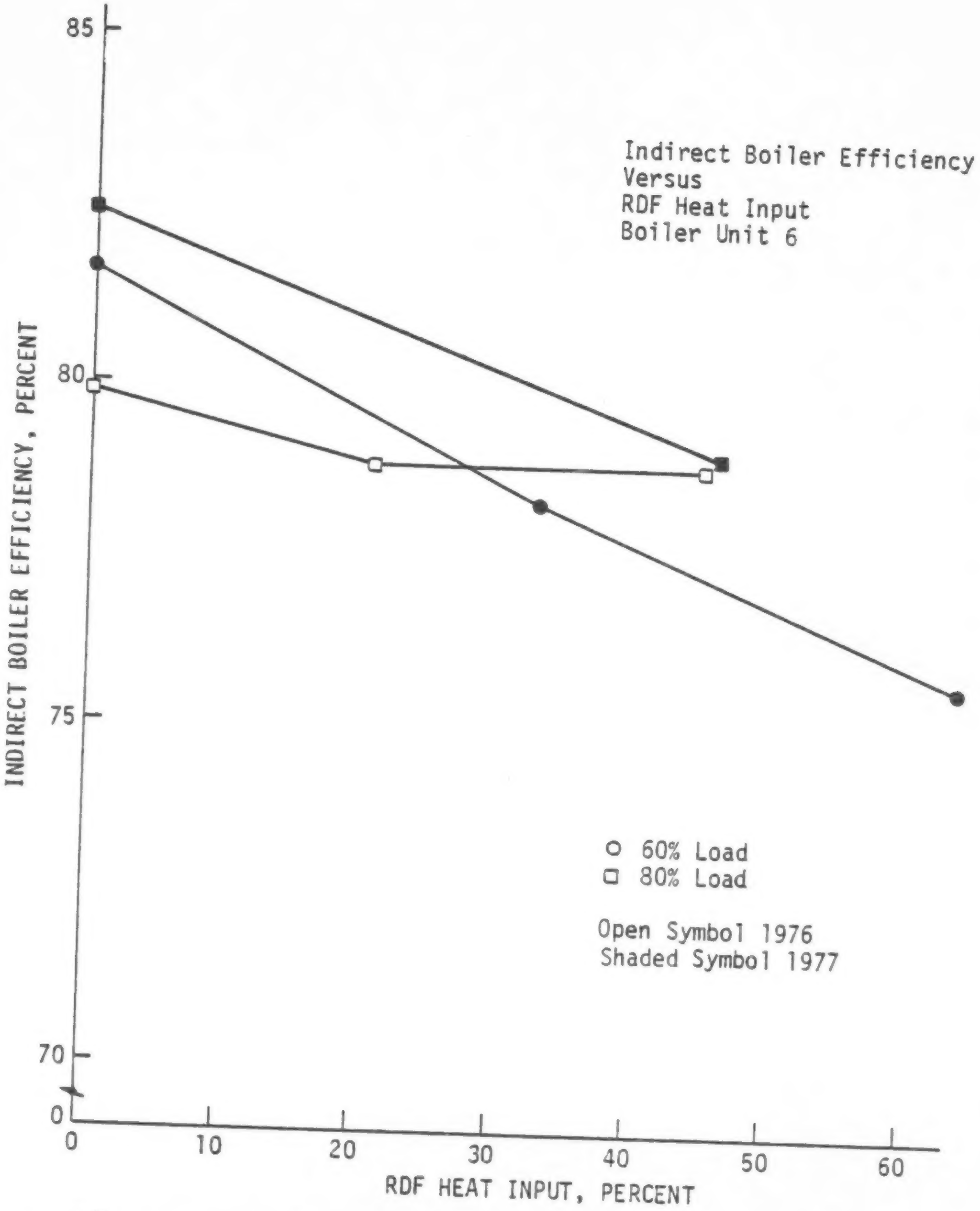

Figure 24 Indirect boiler efficiency of boiler unit 6 as a function of RDF heat input.

TABLE 26. STEAM GENERATOR PERFORMANCE

Year	Nominal load/RDF	Firing rate (kg/h) Coal	Firing rate (kg/h) RDF	Fuel heat input (GJ/h)	Boiler efficiency[a] (%)	Excess air (%)	Flue gas temp. economizer exit (°C)	Heat lost dry flue gas (%)	Heat lost hydrogen in fuel (%)	Heat lost free moisture in fuel (%)	Fuel utilization heat lost in ash (%) Calculated ash rate (%)	Fuel utilization heat lost in ash (%) Measured ash rate (%)	Heat lost in ash (kJ/kg)
Unit 5													
1976	60/0	4,395	---	92.28	77.31	111.98	197	12.09	3.81	1.786	5.82	4.042	4,960
	60/20	3,440	1,530	92.45	74.08	171.78	208	14.50	3.70	2.448	4.35	4.269	3,820
	60/50	1,656	3,817	87.84	74.24	177.36	203	13.26	4.08	3.220	4.14	4.109	3,330
1976	80/0	5,487	---	115.58	75.51	141.61	207	13.65	3.64	1.836	5.30	4.441	4,720
	80/20	3,845	2,384	114.21	74.78	119.62	220	12.53	4.33	2.478	5.68	5.025	4,680
	80/50	2,930	3,958	114.31	75.75	138.56	216	12.54	3.88	3.084	4.65	3.924	3,740
1977	80/0	5,013	---	112.10	77.55	94.53	226	12.55	3.78	2.101	3.06	3.323	4,880
	80/20	3,170	2,287	104.15	75.24	115.68	234	13.61	4.84	2.325	2.18	3.177	2,830
	80/50	3,188	3,468	117.49	74.26	108.13	236	13.34	5.69	2.650	2.77	3.150	3,160
1976	100/0	6,607	---	139.29	78.73	63.77	210	9.73	3.88	1.718	5.33	5.175	4,580
	100/20	4,657	2,874	134.56	76.95	85.11	215	11.16	4.25	2.488	5.74	4.426	4,400
	100/50	3,851	5,425	143.05	74.05	114.38	218	12.54	4.08	3.806	7.14	4.661	4,850
Unit 6													
1977	60/0	4,613	---	102.51	81.63	131.42	193	10.54	3.32	1.984	1.64	1.670	2,810
	60/20	2,773	2,287	91.47	78.21	152.19	205	11.77	4.63	2.611	1.18	1.841	1,740
	60/50	1,617	4,567	97.75	75.59	163.80	203	12.43	6.38	2.800	1.13	1.914	1,360
1976	80/0	6,602	---	141.72	79.83	87.91	201	10.34	4.47	2.317	2.40	2.302	3,860
	80/20	5,539	2,477	151.25	78.75	121.97	205	11.72	3.72	2.821	2.24	2.101	2,940
	80/50	3,311	6,226	147.53	78.72	136.49	204	10.85	3.06	4.351	2.65	2.258	2,770
1977	80/0	6,510	---	145.15	82.43	89.51	210	9.55	3.02	1.931	2.02	2.436	3,460
	80/50	3,435	4,345	136.22	78.91	119.25	218	10.98	5.19	2.224	1.63	1.921	1.900

[a] Indirect method.

Flue Gas Heat Loss Due to Hydrogen in the Fuel--

The flue gas heat loss due to the hydrogen in the fuel for units 5 and 6 for varying percent RDF heat input are listed in Table 26. This heat loss for unit 5 at all steam loads increased slightly from 3.78% at 0% RDF to 4.28% at 20% RDF, and to 4.43% at 50% RDF heat input. The average heat loss for unit 6 at all steam loads also increased slightly from 3.60% at 0% RDF to 4.18% at 20% RDF, and 4.88% at 50% RDF heat input. No overall significant trends are discernible except that the RDF hydrogen content was higher in 1977 and this may be seen in Table 25.

Flue Gas Heat Loss Due to Free Moisture in Fuel--

Figures 25 and 26 show the flue gas heat loss due to the free moisture in the fuel for units 5 and 6 for varying percent RDF heat input. This heat loss for unit 5 at all steam loads increased from 1.85% at 0% RDF to 2.43% at 20% RDF, and to 3.19% at 50% RDF heat input. The average heat loss due to the fuel free moisture for unit 6 (at all loads) increased from 2.08% at 0% RDF to 2.72 RDF, and to 3.13% at 50% RDF heat input. The moisture content of the RDF is listed in Table 25 and this heat loss is listed in Table 26.

Heat Loss of the Dry Flue Gas--

Figures 27 and 28 show the heat loss of the dry flue gas for units 5 and 6 for varying percent RDF heat input. The average heat loss for unit 5 at all steam loads increased from 12.01% at 0% RDF to 12.95% at 20% RDF, and to 12.92% at 50% RDF heat input. The average heat loss of the dry flue gas for unit 6 at all steam loads increased from 10.14% at 0% RDF to 11.75% at 20% RDF and to 12.92% at 50% RDF heat input. Individual heat loss values for each load test condition are listed in Table 26.

Mechanical Collector Efficiency

Figures 29 and 30 depict the effect of percentage RDF heat input and percentage steam load on particulate collector efficiency for the stoker units 5 and 6.

The efficiency is affected by grain loading, sizing, and flue gas volume flow rate into the mechanical collector. Generally, the efficiency is increased by RDF firing and can be attributed to the presence of larger particles of RDF. The unit 5 collector efficiency in 1976 was highest for the 80% steam load and increased from 80.6% at 0% RDF to 90.2% at 20% RDF and to 91.2% at 50% RDF. Because of the change from Iowa coal in 1976 to Iowa-Wyoming coal in 1977, another set of tests at 80% steam load was conducted. Lower efficiencies resulted, and the values increased from 75.0% at 0% RDF to 76.3% at 20% RDF and 76.2% at 50% RDF.

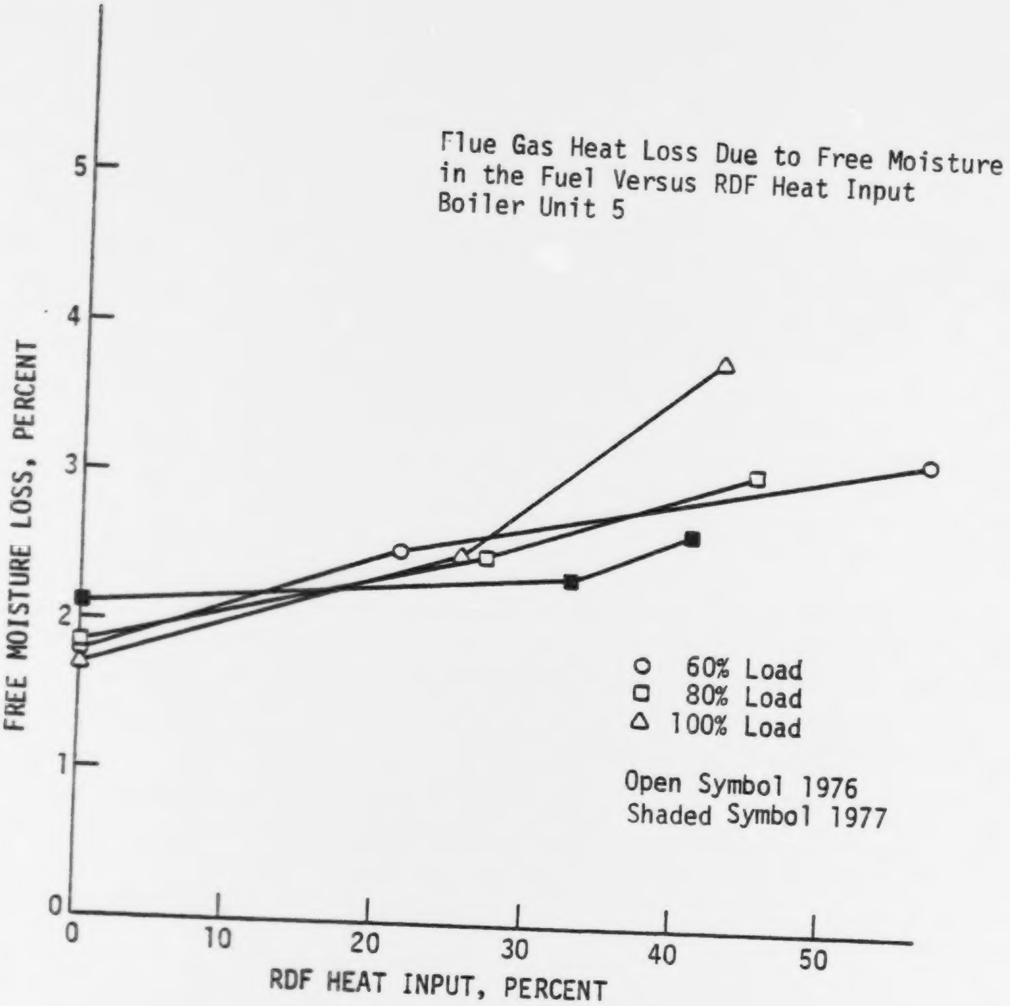

Figure 25. Heat loss of moisture in the flue gas for boiler unit 5 as a function of RDF heat input.

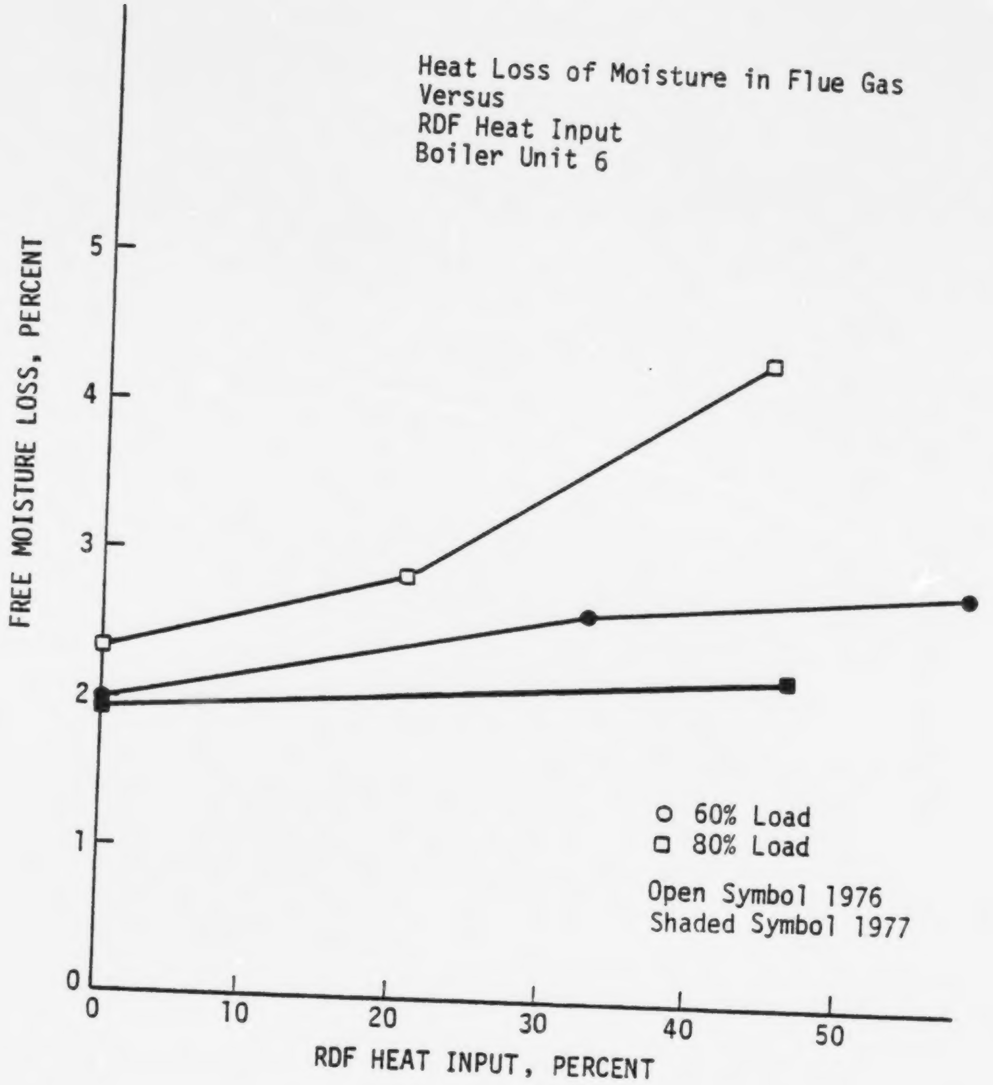

Figure 26. Heat loss of moisture in the flue gas for boiler unit 6 as a function of RDF heat input.

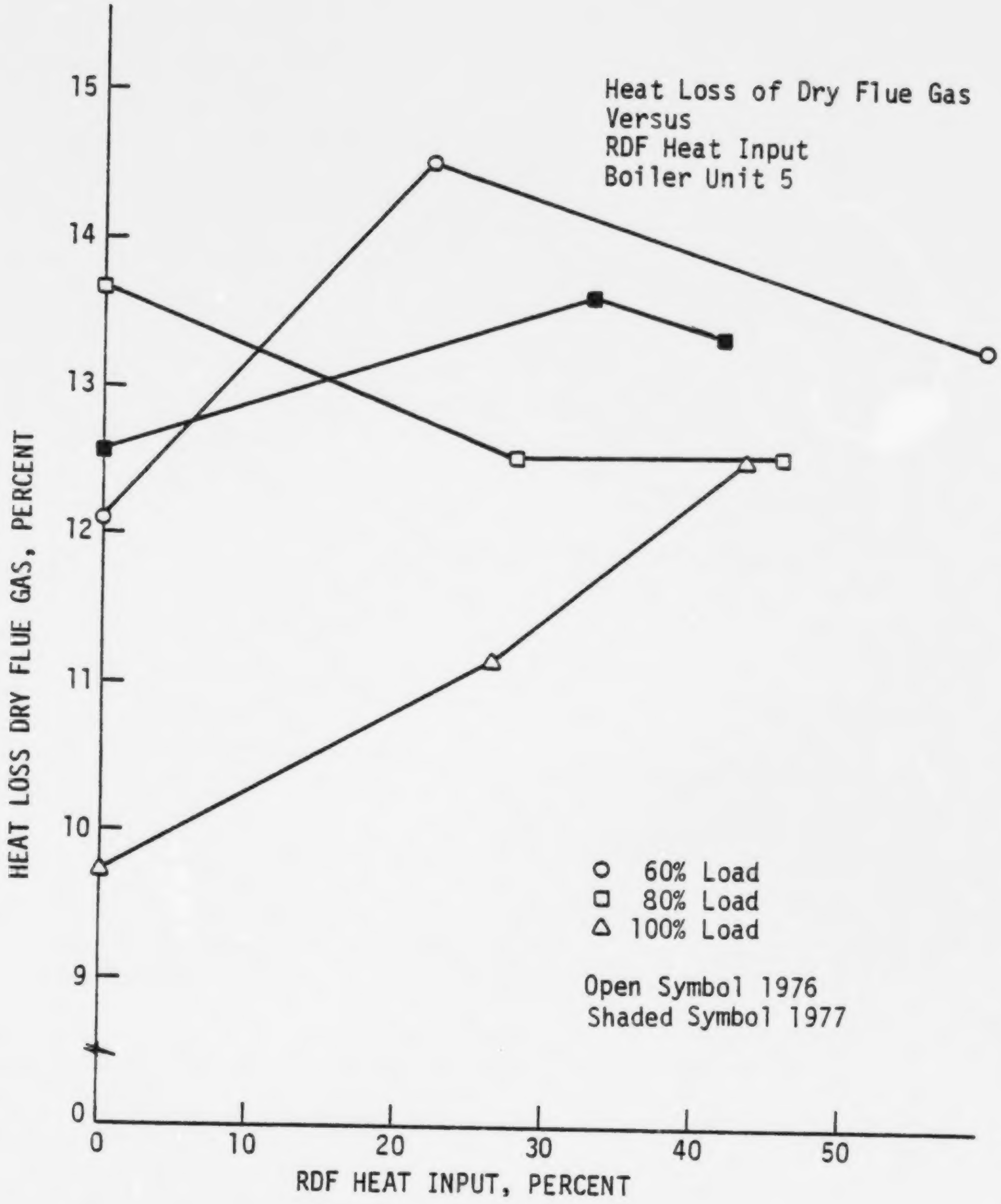

Figure 27. Heat loss of dry flue gas for boiler unit 5 as a function of RDF heat input.

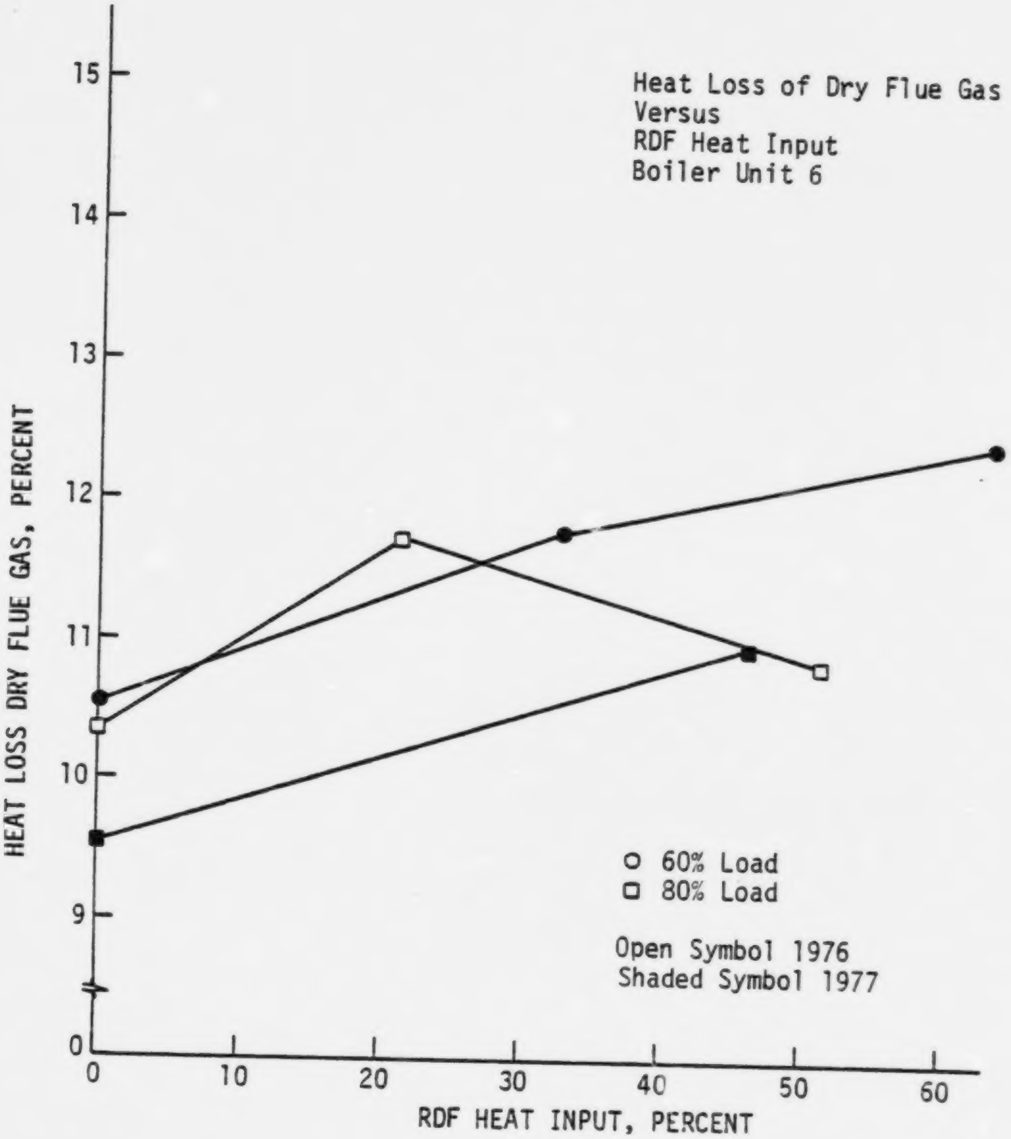

Figure 28. Heat loss of dry flue gas for boiler unit 6 as a function of RDF heat input.

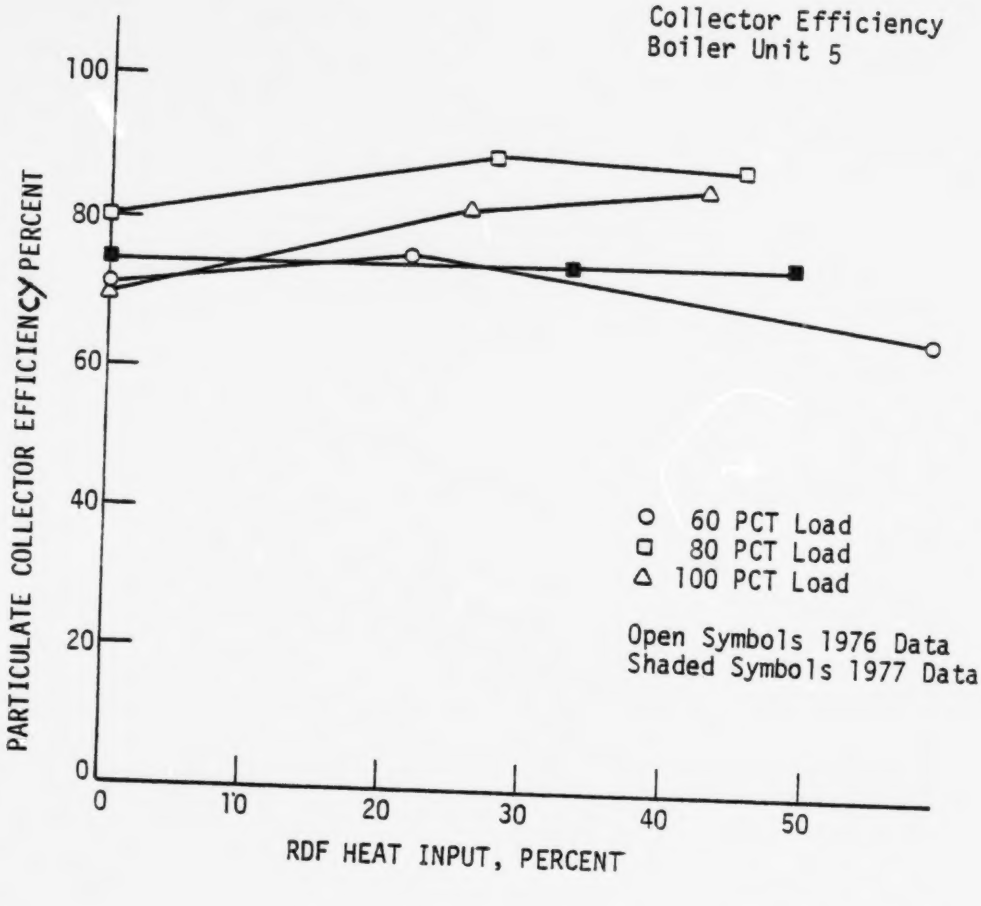

Figure 29. Mechanical (particulate) collector efficiency of boiler unit 5 as a function of RDF heat input.

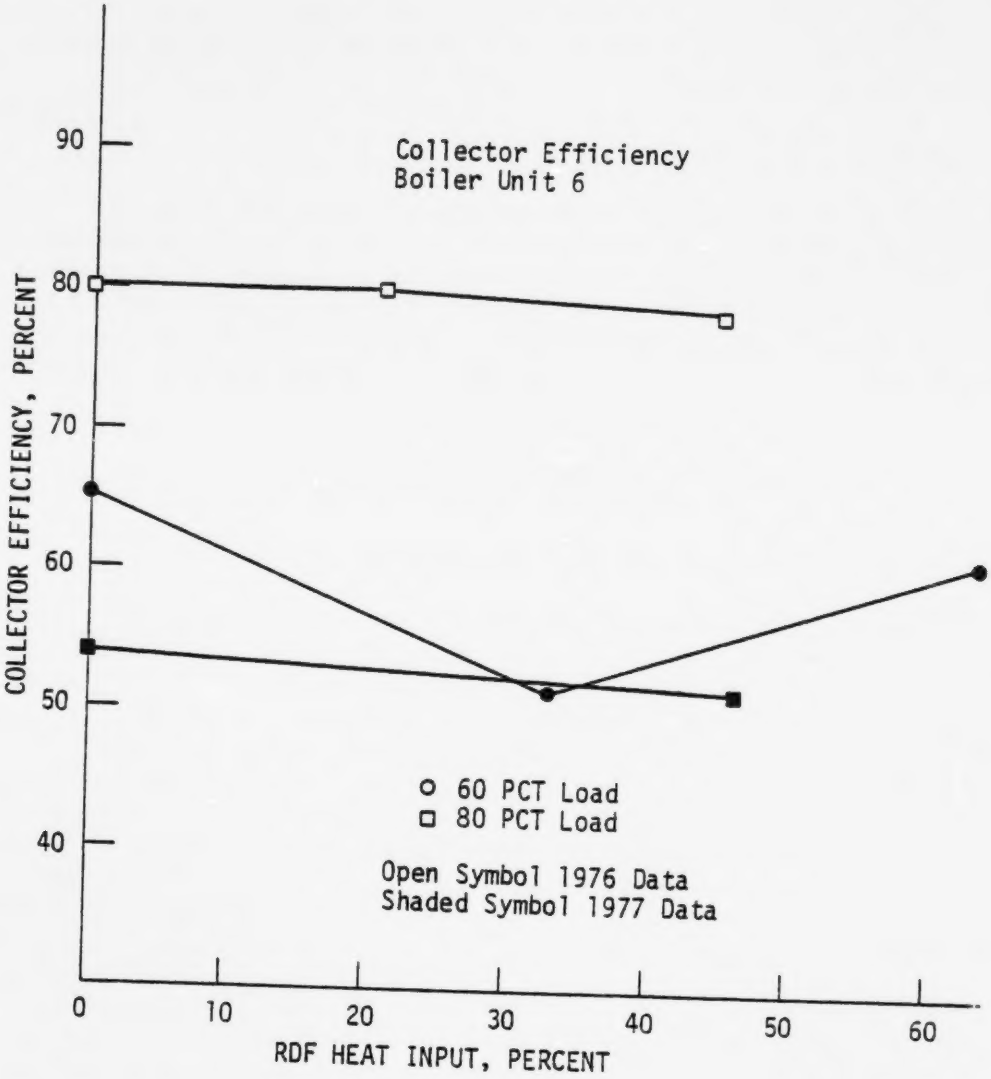

Figure 30. Mechanical (particulate) collector efficiency of boiler unit 6 as a function of RDF heat input.

Examination of excess air values given in Table 26 reveals the amount supplied in the tests for each year. Mechanical collector efficiency for unit 6 at 80% steam load in 1976 remained fairly constant at 80% for all RDF percentage heat inputs. In 1977, using coal sized for stoker firing, the collector efficiency dropped to 55.6% at 0% RDF and 51.3% at 50% RDF. This behavior is still under investigation.

Fuel Utilization

Figures 31 and 32 relate the percentage of total fuel heat input lost dur to combustible remaining in the ash as a function of percentage heat input for units 5 and 6 and are computed based on calculated ash flow rates from the grate hopper and collector hopper. Figures 33 and 34 depict the combustible loss for units 5 and 6 based on measurements of the grate ash and hopper ash flow rates. Thus, the lower the heat loss value, defined as

$$\text{Loss} = \frac{\text{fuel heating value in ash (kJ/h)}}{\text{fuel heat input (kJ/h)}}$$

the better the fuel utilization (or combustion efficiency).

Although there are some differences in the losses calculated by the two methods of analysis, the trends as a function of percentage RDF and steam load are similar. There were no significant changes in the percentage of total heat input lost as the percentage RDF heat input increased from 0% to 50% RDF. The average heat loss for unit 5 was 4.7% using calculated ash flow rates and 4.1% using measured ash flow rates. The average heat loss due to combustibles in the ash for unit 6 was 1.9% based on calculated flow rates and 2.1% based on measured ash flow rates. The heat lost in the ash was also calculated on a per unit weight ash and is listed in Table 26. Using this reference basis, the heat lost in the ash decreased in most cases as the percentage RDF heat input increased.

Fuel Characterization--

Table 25 lists the ultimate analyses of the coal and RDF supplied to units 5 and 6 during the tests in 1976 and 1977. In unit 5, Iowa coal was used in 1976 and a 50-50 mixture of Iowa-Wyoming coal was used in 1977. Unit 6 used Iowa-Wyoming coal mixtures both years. The Iowa coal had an average heating value of 21,197 kJ/kg, while the Iowa-Wyoming coal mixture has an average heating value of 21,600 kJ/kg in 1976 and 22,030 kJ/kg in 1977. The RDF had an average heating value of 12,742 kJ/kg in 1976 and 14,209 kJ/kg in 1977. The moisture content of the Iowa coal was 13.5%, while that for the Iowa-Wyoming coal was 17.8%. The average moisture content of RDF was 23.7% in 1976 and 15.0% in 1977. The average ash content of the Iowa coal was 19.6%; and of the Iowa-Wyoming coal, 11.9%.

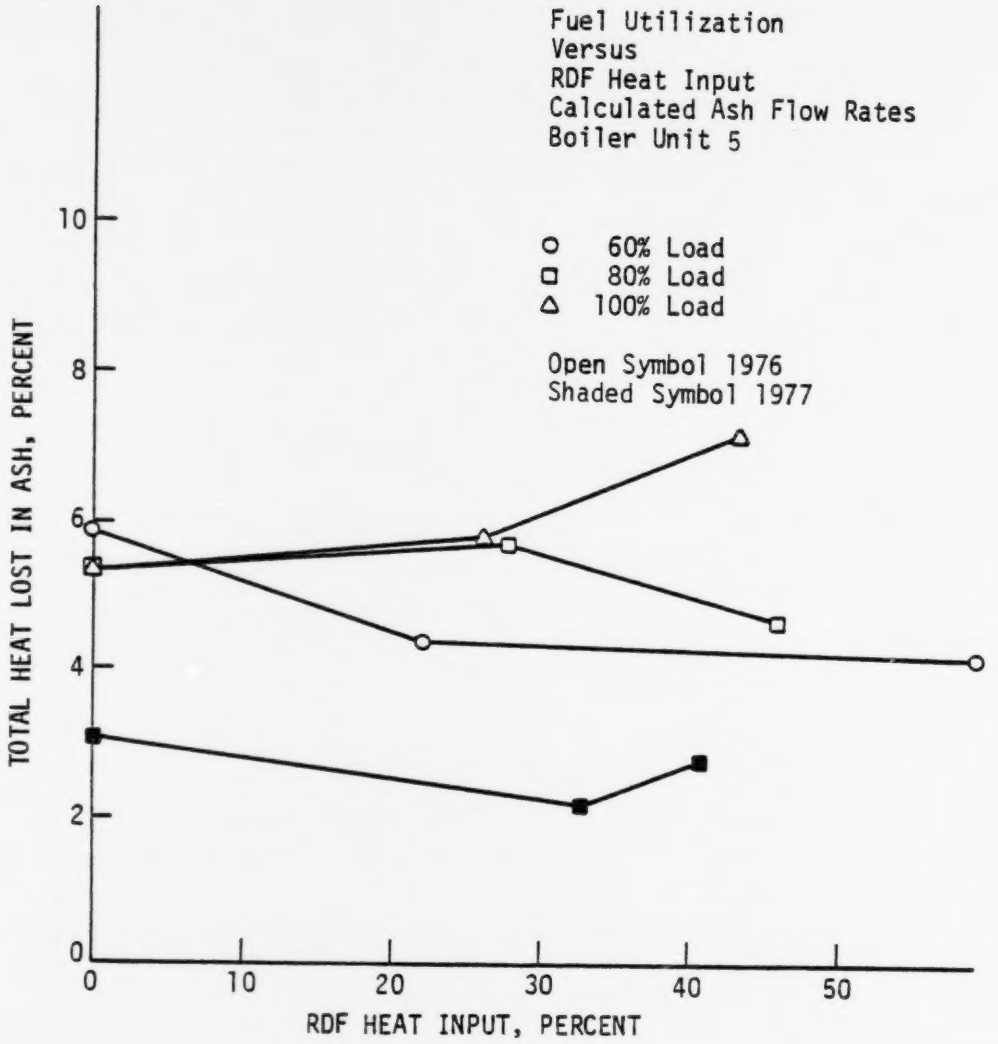

Figure 31. Fuel utilization of boiler unit 5 as a function of RDF heat input as determined from calculated ash flow rates.

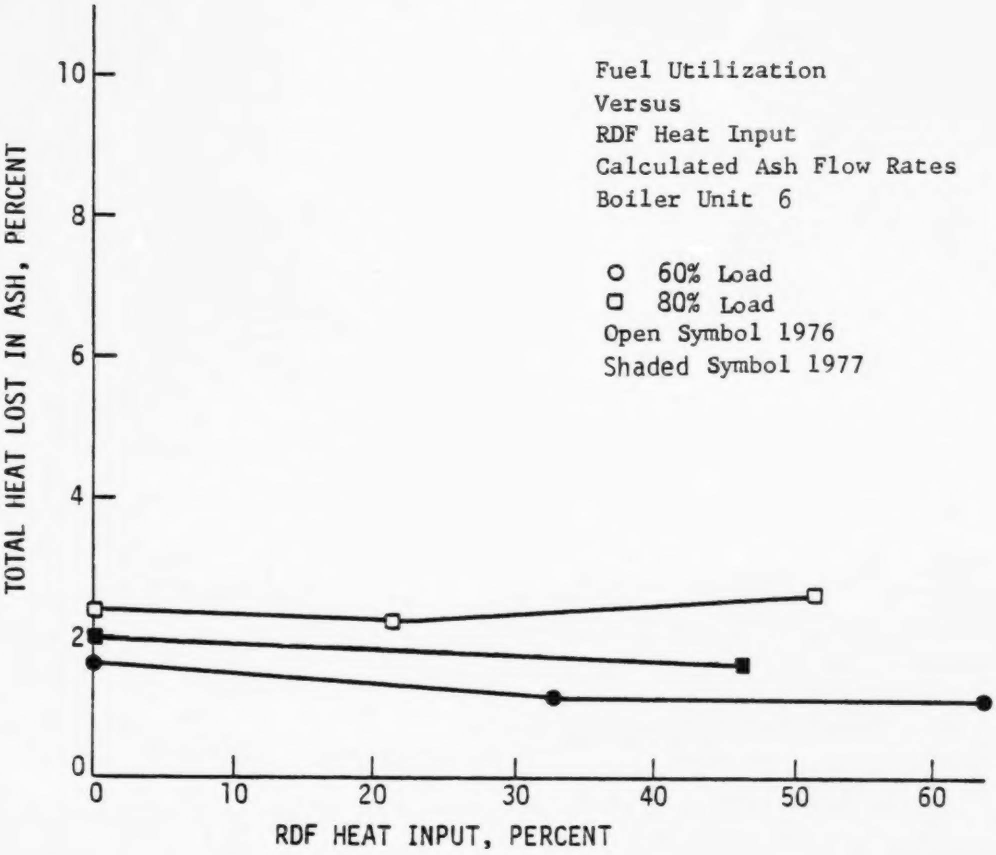

Figure 32. Fuel utilization of boiler unit 6 as a function of RDF heat input, as determined from calculated ash flow rates.

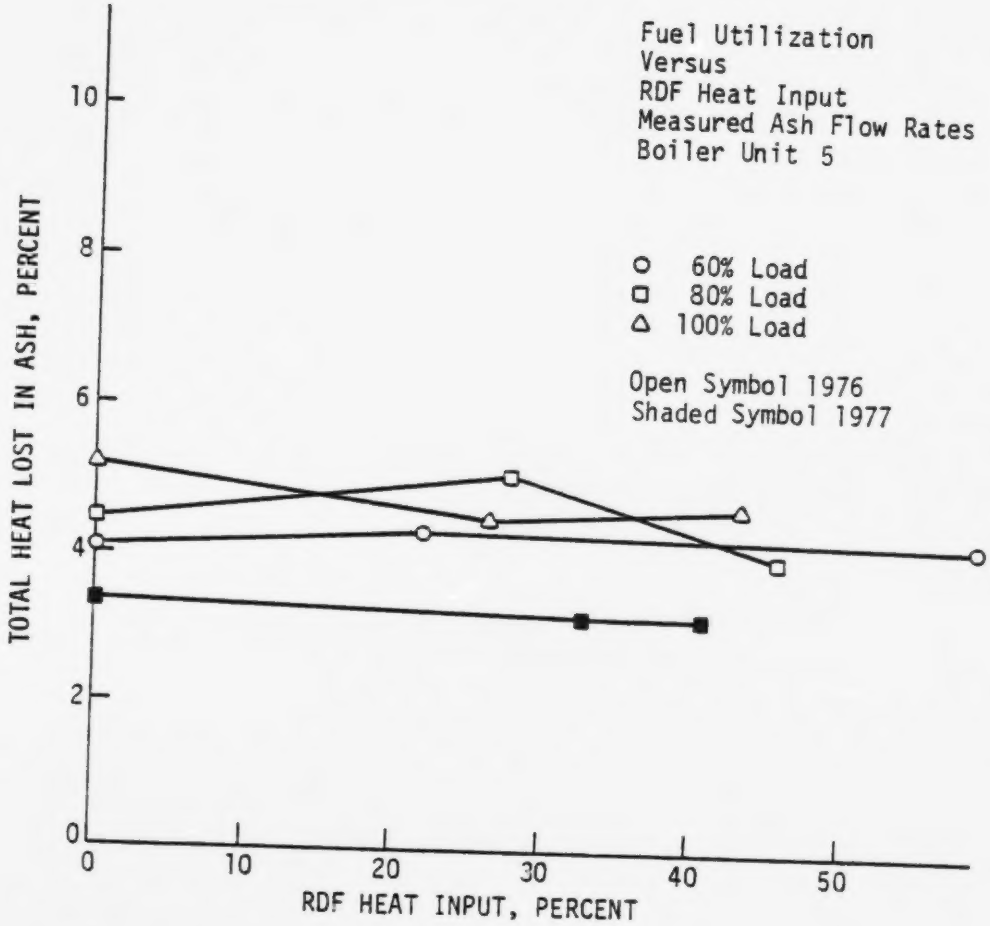

Figure 33. Fuel utilization of boiler unit 5 as a function of RDF heat input as determined from measured ash flow rates.

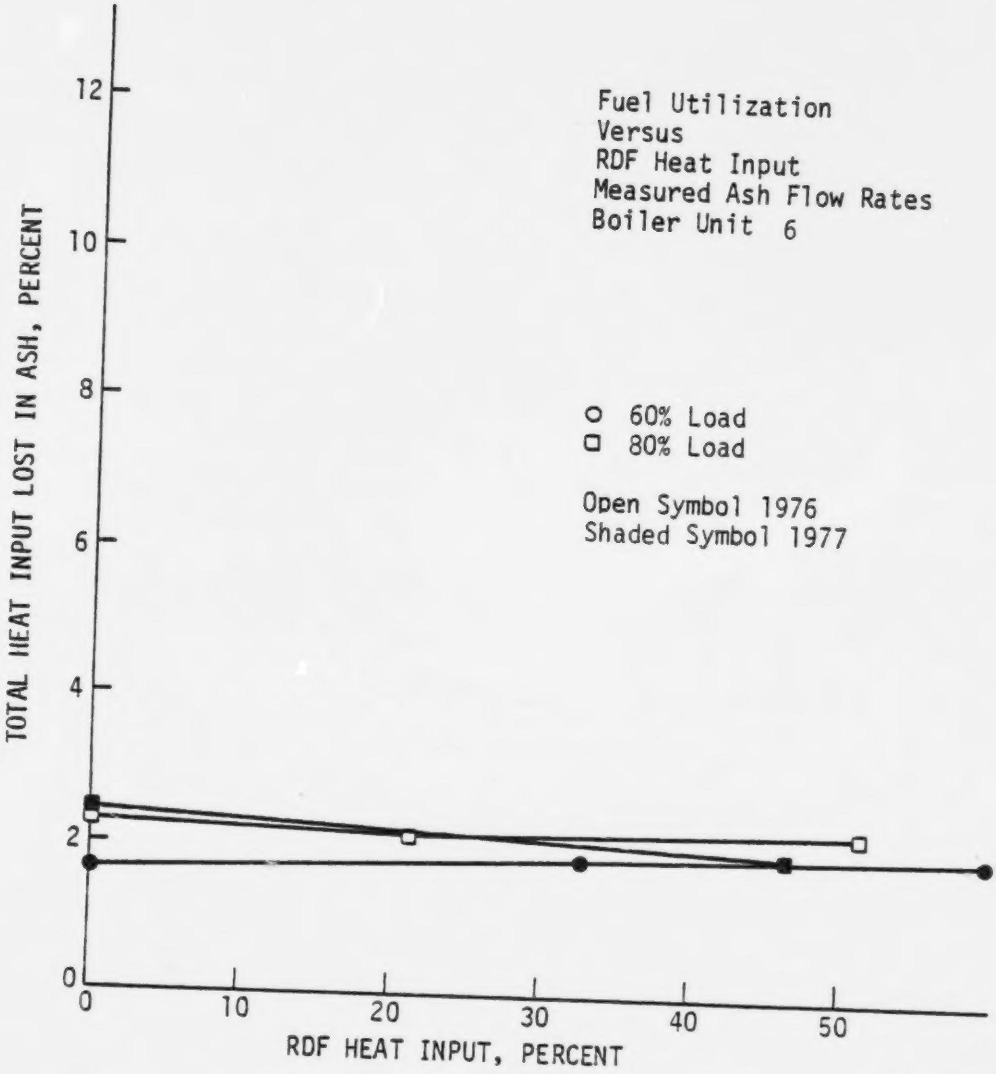

Figure 34. Fuel utilization of boiler unit 6 as a function of RDF heat input as determined from measured ash flow rates.

The average ash content of the RDF was 15.9% in 1976 and 13.5% in 1977. The average chlorine content of the coal was 0.05%, and that for the RDF was 0.30%.

Ash Ultimate Analysis--

Tables 27 and 28 list the ultimate analyses for the grate and collector hopper ash for units 5 and 6. The most noticeable change with increase in RDF heat input is the decrease in the carbon content of the fly ash collected in the mechanical hopper. As mentioned previously, this results in a lower heat loss in the ash per kilogram of ash. Thus, more complete burning with RDF does occur.

Chemical Analysis of Ash

Table 29 lists the nine major trace elements of the mineral ash for coal, RDF, grate ash, and hopper ash. These elements are aluminum (Al), silicon (Si), titanium (Ti), potassium (K), iron (Fe), sodium (Na), magnesium (Mg), and phosphorus (P) and are expressed as percentage oxides of the mineral ash. The average silica content of the RDF is 46.94% compared to a value of 35.3% for the coal. The silica content of the fly ash removed by mechanical collector is higher than that for the grate ash in unit 5 but not for unit 6. The higher silica content in the RDF is attributed to the presence of ground glass.

The sodium content of the RDF is also higher than that for coal, which affects the fouling index. The average sodium content for the Iowa coal was 0.18%; and for the Iowa-Wyoming coal, 0.71%. The average RDF sodium content was 5.40%.

Slagging-Fouling Indices

Potential slagging and fouling problems in the furnace and convection sections of a boiler are dependent on the major chemical elements of the mineral ash (oxide form).

The fouling indices for RDF grate and hopper ash are greater than one, indicating potential for fouling (or deposition of material) in the convection section. A slagging index from 3.0 to 2.6 indicates the potential for high slagging. It should be noted that this occurs for the Iowa and Iowa-Wyoming mixture coal. Since Iowa coal has a high sulfur content and the factor is dependent on sulfur content, high factors would result.

Ash Fusion Temperatures

Ash fusion temperature averages of the coal, RDF, grate ash, and mechanical collector hopper ash are listed in Table 30.

TABLE 27. ANALYSIS OF BOTTOM AND COLLECTOR ASH[a] FROM BOILER UNIT 5

Parameter (units)	80% load 1976 Iowa coal with			80% load 1977 Iowa-Wyoming coal with		
	0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
Mineral ash, %	87.60 (84.44)	82.43 (88.29)	90.15 (88.85)	91.95 (78.55)	93.08 (88.32)	90.00 (90.52)
Carbon, %	8.81 (12.89)	13.01 (7.61)	6.84 (8.14)	6.07 (19.39)	5.53 (9.99)	8.04 (7.73)
Hydrogen, %	0.67 (0.61)	0.92 (0.43)	0.77 (0.67)	0.17 (0.25)	0.21 (0.14)	0.28 (0.14)
Sulfur, %	2.92 (1.98)	3.54 (3.66)	2.24 (2.33)	1.79 (1.80)	1.17 (1.51)	1.65 (1.58)
Chlorine, %	--- ---	--- ---	--- ---	0.02 (0.00)	0.02 (0.03)	0.04 (0.03)

Parameter (units)	60% load 1976 Iowa coal with			100% load 1976 Iowa coal with		
	0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
Mineral ash, %	87.06 (84.71)	88.46 (89.57)	89.77 (95.10)	86.91 (79.47)	85.96 (88.10)	85.04 (88.06)
Carbon, %	8.59 (12.83)	7.50 (7.70)	7.01 (3.37)	9.44 (17.97)	9.64 (8.74)	11.16 (8.60)
Hydrogen, %	0.87 (0.65)	0.86 (0.60)	0.90 (0.51)	0.77 (0.53)	0.63 (0.56)	0.70 (0.81)
Sulfur, %	3.49 (1.82)	3.18 (2.14)	2.31 (1.03)	2.87 (2.04)	3.75 (2.61)	3.12 (2.53)

[a] Items in parentheses are for collector ash.

TABLE 28. ANALYSIS OF BOTTOM AND COLLECTOR ASH[a] FROM BOILER UNIT 6

Parameter (units)	80% load 1976 Iowa-Wyoming coal with			80% load 1977 Iowa-Wyoming coal with	
	0% RDF	20% RDF	50% RDF	0% RDF	50% RDF
Mineral ash, %	93.48 (84.75)	94.79 (87.97)	96.09 (87.19)	93.86 (81.87)	96.06 (91.79)
Carbon, %	3.77 (12.93)	2.84 (9.51)	2.31 (10.17)	4.30 (16.59)	2.74 (6.95)
Hydrogen, %	0.81 (0.64)	0.71 (0.58)	0.51 (0.85)	0.23 (0.21)	0.19 (0.18)
Sulfur, %	1.95 (1.68)	1.65 (1.94)	1.09 (1.79)	1.58 (1.33)	0.99 (1.07)
Chlorine, %	--- ---	--- ---	--- ---	0.04 (0.01)	0.03 (0.03)

Parameter (units)	60% load 1977 Iowa-Wyoming coal with		
	0% RDF	20% RDF	50% RDF
Mineral ash, %	96.76 (85.48)	96.72 (91.84)	96.78 (84.23)
Carbon, %	2.04 (12.48)	2.23 (6.49)	2.32 (4.45)
Hydrogen, %	0.13 (0.23)	0.12 (0.17)	0.16 (0.13)
Sulfur, %	1.06 (1.76)	0.90 (1.48)	0.71 (1.03)
Chlorine, %	0.01 (0.02)	0.03 (0.02)	0.02 (0.06)

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[a] Items in parentheses are for collector ash.

TABLE 29 CHEMICAL ANALYSIS OF ASH[a]

	Year	Al_2O_3	SiO_2	TiO_2	K_2O	CaO	Fe_2O_3	Na_2O	MgO	P_2O_5	Slagging Index	Fouling Index
Unit 5												
Coal	1976	19.70	38.01	0.60	1.07	17.29	22.29	0.18	0.49	0.36	5.370	0.135
	1977	12.18	31.97	1.03	1.19	11.82	23.89	0.63	1.35	0.33	2.607	0.536
RDF	1976	16.14	44.16	2.26	2.42	21.55	5.08	5.25	2.50	0.64	0.377	3.081
	1977	11.71	47.70	1.65	1.74	12.74	5.89	5.58	2.55	0.84	0.972	2.605
Grate Ash	1976	11.36	33.63	0.72	1.31	29.46	24.52	1.69	1.07	0.43	4.302	2.191
	1977	12.86	44.29	1.33	1.17	12.91	20.20	3.34	2.05	0.49	0.979	2.13
Hopper Ash	1976	14.99	39.33	1.17	2.00	20.90	18.06	1.56	1.48	0.63	1.851	1.182
	1977	10.66	47.43	1.27	1.49	13.89	14.60	2.82	2.12	0.56	1.044	1.562
Unit 6												
Coal	1976	18.85	37.94	0.91	1.04	17.82	20.39	0.73	1.72	0.59	2.900	0.522
	1977	13.68	33.21	0.79	1.13	12.17	20.93	0.78	1.71	0.45	2.269	0.611
RDF	1976	16.43	45.60	2.24	2.46	19.31	5.38	5.24	2.58	0.78	0.250	2.874
	1977	12.39	50.32	1.81	1.74	11.64	4.55	5.49	2.42	0.76	0.195	2.20
Grate Ash	1976	13.09	42.01	0.88	1.35	19.65	18.27	2.68	1.87	0.60	1.233	1.871
	1977	14.64	45.58	1.11	1.26	11.76	18.30	3.54	1.85	0.52	0.663	1.531
Collector Ash	1976	15.37	37.33	1.38	1.97	21.82	17.38	1.87	2.14	0.76	1.549	1.495
	1977	15.10	45.79	1.34	1.54	13.07	13.21	2.58	2.15	0.63	0.710	1.396

[a] Expressed as % of mineral ash.

TABLE 30. AVERAGE ASH FUSION TEMPERATURES

		Reducing atmosphere (°C)				Oxidizing atmosphere (°C)			
	Year	IT	ST	HT	FT	IT	ST	HT	FT
Unit 5									
Coal	1976	1165	1181	1188	1196	1241	1250	1257	1268
	1977	1153	1163	1172	1184	1227	1246	1258	1273
RDF	1976	1101	1147	1168	1211	1145	1165	1183	1232
	1977	1153	1166	1176	1188	1173	1184	1194	1204
Grate Ash	1976	1108	1120	1129	1133	1188	1204	1215	1232
	1977	1127	1135	1149	1159	1211	1222	1234	1248
Collector Ash	1976	1101	1113	1125	1028	1182	1192	1203	1218
	1977	1139	1146	1157	1170	1194	1204	1214	1223
Unit 6									
Coal	1976	1155	1160	1163	1167	1228	1232	1236	1240
	1977	1192	1203	1213	1222	1257	1273	1282	1393
RDF	1976	1104	1128	1139	1158	1147	1162	1173	1194
	1977	1160	1167	1175	1216	1183	1191	1199	1208
Grate Ash	1976	1075	1099	1115	1139	1189	1199	1211	1223
	1977	1120	1128	1136	1144	1202	1210	1218	1226
Collector Ash	1976	1110	1117	1126	1135	1200	1209	1217	1229
	1977	1171	1181	1194	1204	1211	1222	1234	1249

ASTM Method D-1857

Nomenclature

IT = Initial deformation temperature
ST = Softening temperature (H = W)

HT = Hemispherical temperature ($H = \frac{W}{2}$)
FT = Fluid temperature
H = Cone height
W = Cone width

No specific correlation of behavior has been determined so far. The initial deformation temperatures (IT) of the coal ash under reducing and oxidizing atmospheres were 1164°C and 1237°C, respectively. The initial deformation temperature average values for the RDF ash were 1103°C and 1146°C for 1976 and 1157°C and 1178°C for 1977. The RDF ash fusion temperatures under an oxidizing atmosphere were generally lower than those for coal ash. A comparison of initial fusion temperatures, under a reducing atmosphere, for unit 5 at 80% steam load is shown in Figure 35 At 50% RDF heat input, fusion temperatures of grate ash and hopper ash are lower than those for coal and RDF.

Ash Flow Rates

Measured grate, mechanical collector, and stack ash flow rates at 80% steam load for units 5 and 6, expressed as kilograms of ash per 100 kg of steam flow, are shown in Figures 36 and 37. The ash accumulation flow rate is also shown in Table 31. Collector ash flow rates decreased slightly for unit 5 and remained constant for unit 6; grate ash and stack emissions increased with RDF heat input for units 5 and 6.

Fuel Sizing Data

Measured fuel sizing data for the coal and RDF are shown in Table 32.

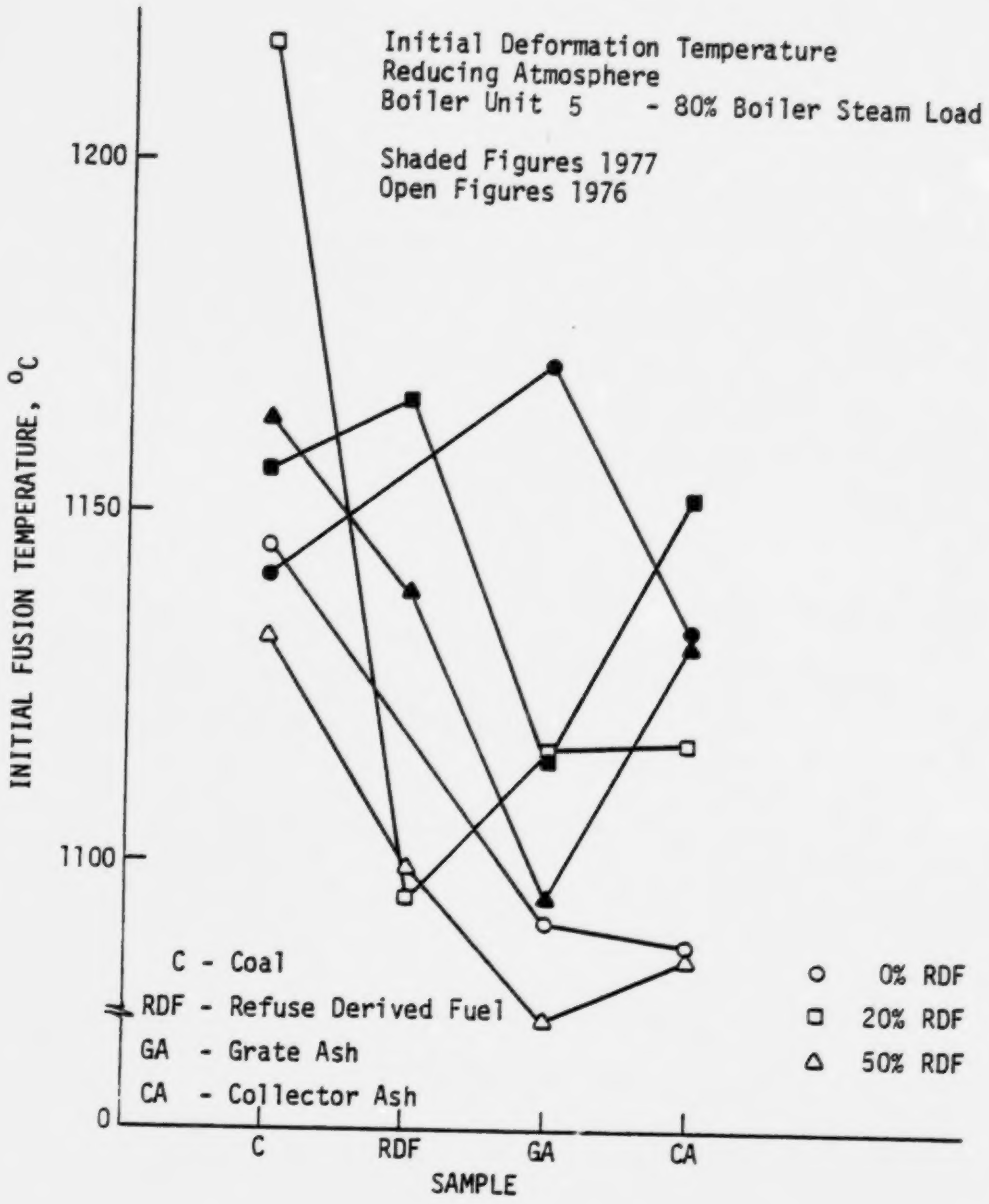

Figure 35. Initial deformation temperature under reducing atmosphere for fuel and ash for boiler unit 5 at 80% steam load.

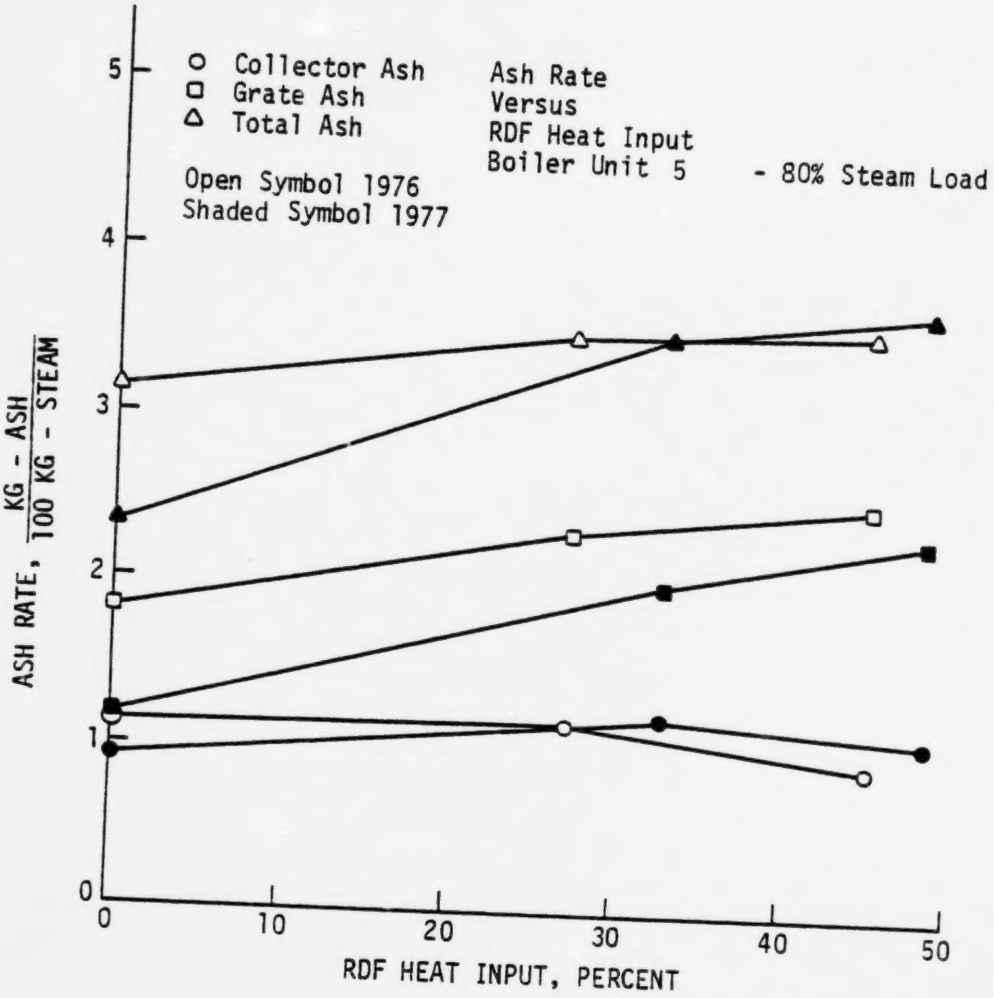

Figure 36. Ash rate of boiler unit 5 as a function of RDF heat input at 80% steam load.

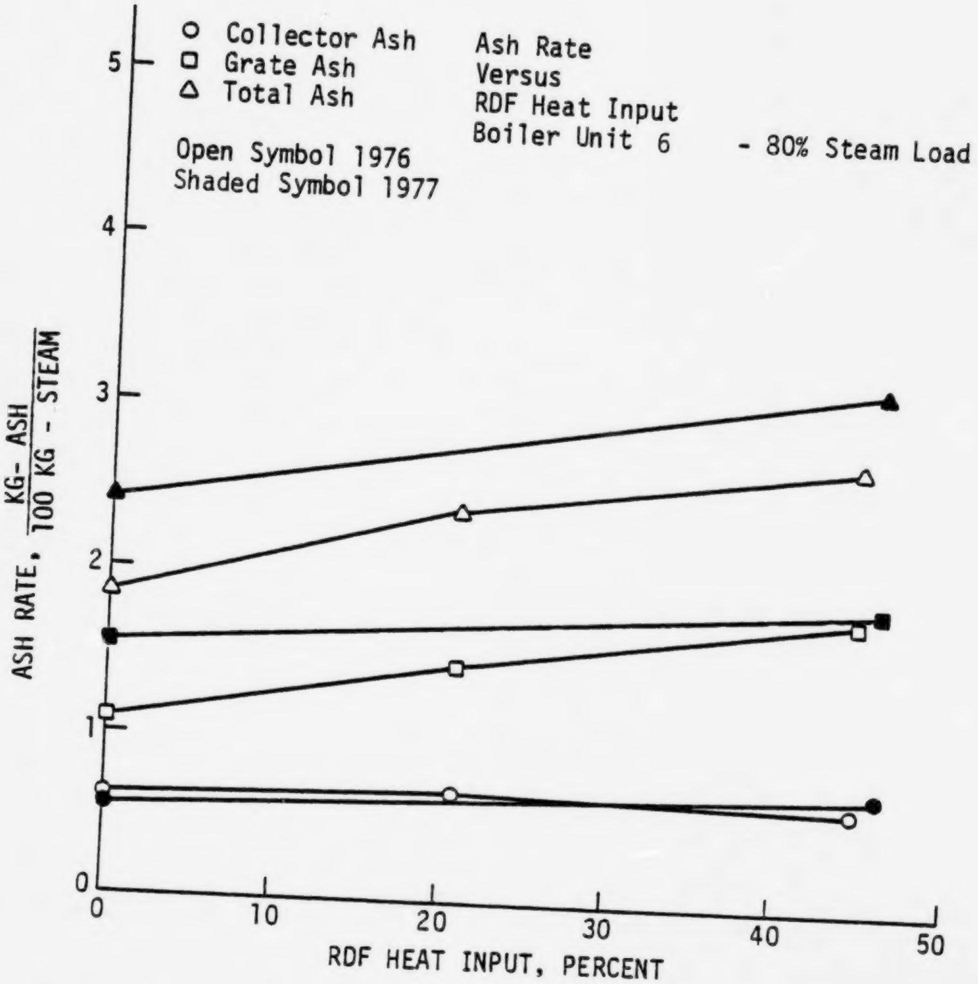

Figure 37. Ash rate of boiler unit 6 as a function of RDF heat input at 80% steam load.

TABLE 31. ASH ACCUMULATION FLOW RATE (kg/100 kg of steam flow)

Year	Load/RDF	Grate ash	Collector ash	Total[a]
Unit 5				
1976	60/0	1.884	0.615	2.85
	60/20	2.447	1.195	4.02
	60/50	2.983	0.78	4.20
1976	80.0	1.82	1.12	3.14
	80/20	2.29	1.16	3.57
	80/50	2.49	0.92	3.52
1977	80/0	1.13	0.94	2.33
	80/20	1.20	2.20	3.47
	80/50	2.61	1.06	3.95
1976	100/0	1.957	1.094	3.81
	100/20	2.67	0.53	3.31
	100/50	2.58	0.68	3.39
Unit 6				
1977	60/0	1.04	0.81	2.07
	60/20	1.81	0.92	3.28
	60/50	2.99	1.29	4.85
1976	80/0	1.09	0.62	1.86
	80/20	1.45	0.69	2.38
	80/50	1.76	0.63	2.70
1977	80/0	1.54	0.58	2.41
	80/50	1.84	0.73	3.16

[a] Includes stack emissions.

TABLE 32. FUEL SIZING DATA

Coal			RDF	
Size, mm	1977 %	Size, mm	1976 %	1977 %
<19.0	95.26	>63	6.96	3.68
12.5	88.16	<63	93.04	96.32
9.5	75.63	38.1	84.60	86.98
4.75	53.00	19.0	66.09	65.51
2.36	35.60	9.5	36.13	37.01
1.18	23.48	4.8	18.57	20.27
0.60	14.10	d_m[a]	13.1	12.16
0.30	8.65			
0.15	4.52			
0.075	2.88			

[a] d_m = geometric mean diameter in millimeters.

SECTION 6

ENVIRONMENTAL EMISSIONS OF THE STOKER-FIRED BOILERS

FACILITIES

Table 24 in the preceding section includes descriptive characteristics of the Ames stoker-fired steam generators (units 5 and 6) used for the tests. Both units have dry pneumatic vacuum bottom and fly ash removal systems. Mechanical dust collectors are the only type of air pollution control equipment installed on units 5 and 6. Unit 7, the pulverized coal unit, is not described since testing on that unit is in progress.

EXPERIMENTAL DESIGN

For this study, the independently controlled variables were load, based on steam flow, and refuse-derived fuel (RDF) quantity, based on heat energy input to the boiler. Nominal load levels selected were 60, 80, and 100% of rated capacity; RDF quantities were 0, 20, and 50% of heat energy input.

For each steam flow and each quantity of RDF, three experimental runs were accomplished for statistical purposes. For unit 5 the statistical design was 3 x 3 x 3 full factorial experiment with 27 runs needed to fill the data matrix of the experiment. These experimental runs were accomplished during 1976. After observing the operation of unit 5, a steam load of 80% was chosen as typical of boiler demand. Also at 80% load wall slagging was reduced, and excess air supplied for the coal and RDF combustion was optimum. Therefore, nine additional tests selected at 80% load were accomplished on unit 6. Testing of two boilers of similar type but different size allowed the investigators to observe whether boiler size had any effect on emissions.

For the runs accomplished in 1976, unit 5 was fueled with mixtures of Iowa (high sulfur) coal and RDF (low sulfur). A 50-50 mixture of Iowa and Wyoming coal (mixture burned to meet sulfur emission standards and for economic benefits) and RDF was the fuel combination used in unit 6.

During 1977 additional runs were accomplished on units 5 and 6. At 80% load, nine tests on unit 5 were accomplished using an Iowa-Wyoming coal mixture with RDF similar to that used on unit 6 during the 1976 runs.

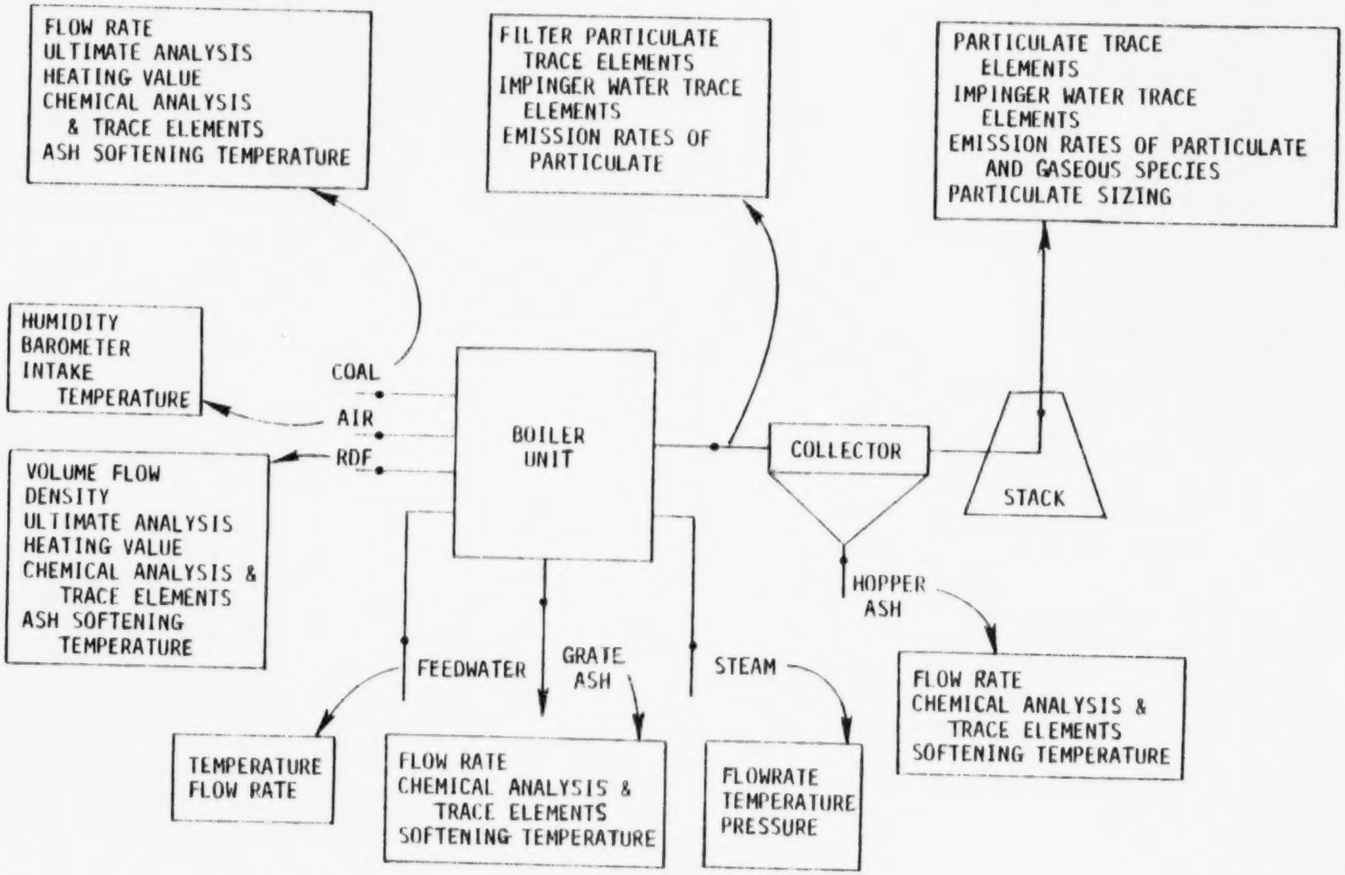
FLOW RATE
ULTIMATE ANALYSIS
HEATING VALUE
CHEMICAL ANALYSIS
& TRACE ELEMENTS
ASH SOFTENING TEMPERATURE
FILTER PARTICULATE
TRACE ELEMENTS
IMPINGER WATER TRACE
ELEMENTS
EMISSION RATES OF
PARTICULATE
PARTICULATE TRACE
ELEMENTS
IMPINGER WATER TRACE
ELEMENTS
EMISSION RATES OF PARTICULATE
AND GASEOUS SPECIES
PARTICULATE SIZING
HUMIDITY
BAROMETER
INTAKE
TEMPERATURE
COAL
AIR
RDF
BOILER
UNIT
COLLECTOR
STACK
VOLUME FLOW
DENSITY
ULTIMATE ANALYSIS
HEATING VALUE
CHEMICAL ANALYSIS &
TRACE ELEMENTS
ASH SOFTENING
TEMPERATURE
HOPPER
ASH
FEEDWATER
GRATE
ASH
STEAM
FLOW RATE
CHEMICAL ANALYSIS &
TRACE ELEMENTS
SOFTENING TEMPERATURE
TEMPERATURE
FLOW RATE
FLOW RATE
CHEMICAL ANALYSIS &
TRACE ELEMENTS
SOFTENING TEMPERATURE
FLOWRATE
TEMPERATURE
PRESSURE

Figure 38. Sample locations and items sampled.

Also during 1977, nine tests on unit 6 were accomplished at 60% load. An additional four tests (two at 0% RDF and two at 50% RDF) were accomplished at 80% load on unit 6 to compare 1976 operation with 1977 operation.

TESTING AND SAMPLING PROCEDURE

The average test duration was 4 to 5 hr. However, some tests exceeded 8 hr, and there were back-to-back tests on some days. Sampling of effluents was conducted according to EPA-prescribed techniques (8, 9, 10). Stack effluents, including particulate samples, were obtained at numerous prescribed points in the smoke stack cross section. Three sampling trains operated simultaneously. An additional train was located before the particulate collector. Input fuel and grate ash were sampled at regular 1-hr intervals throughout the test period and then mixed to yield a composite sample. Hopper (fly) ash was sampled at the completion of each experimental run. Combustion air to the boiler was monitored by wet and dry bulb thermometry. Steam flow rate, temperature, and pressure were also recorded at regular intervals.

A block diagram showing the sample locations and types of samples collected is included in Figure 38. The sampling was conducted on a regular basis except that of heavy organic species, which were sampled intermittently as manpower, instrumentation, and equipment allowed.

The composite coal and RDF samples were analyzed in the Ames Laboratory. Ultimate analyses and heating values were obtained by standard ASTM methods. Trace elements were determined by x-ray fluorescence (XRF).

The size distribution of the particulates after the dust collector was determined by an Andersen cascade impactor. Particulate samples obtained with the EPA Method 5 sampling train were analyzed by SRF. The impinger solutions from the method 5 train were analyzed with an inductively coupled plasma system (11).

The gases CO_2, CO, O_2, and N_2 in the stack were determined by Orsat techniques. EPA Method 7 was used for evaluation of NO_x levels, and the EPA Method 6 train was used for measurement of SO_x and chlorides. Grab samples of stack gas were obtained for measurement of C_1 through C_5 hydrocarbons by gas chromatography. Several modifications (5, 12) of the EPA Method 5 train were used to collect samples for analysis of aldehydes and ketones, chlorides, mercury, and other trace metallic elements. All inputs to and outputs from each boiler were evaluated including fuel, combustion air, bot-ash, steam, fly ash, and stack gas.

Polynuclear aromatic compounds were sampled by drawing stack gas through a column of macro-reticular resin and also by extraction from particulates collected in the stack. Gas chromatography and mass spectroscopy were used for identification.

RESULTS

The average supply air, feedwater, and steam flow characteristics for all of the experimental runs on units 5 and 6 are tabulated in Tables 33 and 34, respectively.

Characteristics of Input Fuels

The averages for the heating values and ultimate analysis of both the coal and the RDF used during the tests are listed in Table 35. The average amounts of trace elements in both coal and RDF are also given in Table 35. It should be noted that the ash content of the RDF is less than that of the Iowa coal. It was also expected that the high sulfur content of the Iowa coal would be diluted by the RDF, which is very low in sulfur. The average density of the RDF was 115 kg/m^3 (7.2 lb/ft^3).

Characteristics of Grate and Fly Ash

Tables 36 and 37 are tabulations of the combustible and noncombustible constituents of both the grate (bottom) and fly (hopper) ash from unit 5 and unit 6, respectively. The interesting feature of these data is that the characteristics of the fly ash and the bottom ash are significantly different when coal is the only fuel burned in the boiler; but as the fuel mixture changes from 0% RDF to 50% RDF the characteristics of the fly ash and bottom ash become nearly identical. It should also be noted that on a per pound basis there was no significant difference between coal and RDF in percentage of heat energy leaving as combustible in the ash. The average was on the order of 5% for both fuels. However, the RDF pneumatic feeders increased the air supply to the boilers and consequently the excess air leaving the boiler. This increase in excess air resulted in a decrease of boiler efficiency.

Analysis of selected samples of RDF ash indicated that the RDF ash fusion temperatures were from 60 to 100 C lower than those for coal. The RDF also has a higher sodium content which, in turn, has a significant detrimental effect on the fouling index as compared to burning coal only. Thus, some difficulty with slagging and fouling was anticipated and observed during these tests.

Emissions

Tables 38 and 39 give characteristics of selected emissions for boiler units 5 and 6, respectively, as presented in References 5, 7, and 13-18.

TABLE 33. AVERAGE AIR, FEEDWATER, AND STEAM CHARACTERISTICS FOR EXPERIMENTAL RUNS ON BOILER UNIT 5 (1976-1977)

Nominal Load (%)	Nominal RDF (%)	Year		Steam load[a] (%)	RDF Heat input (%)	Air temp. Wet bulb (°C)	Air temp. Dry bulb (°C)	Rel. hum. (%)	Baro. press. (kPa)	Feed-water temp. (°C)	Steam Temp. (°C)	Steam Press. (kPa)	Flue gas (stack) Flow (m^3/s)	Flue gas (stack) Temp. (°C)	Flue gas (stack) Press. (kPa)
60	0	1976	$\bar{x}$ [b]	59.6	0.00	20	30	46	97.87	147	443	4298	14.89	444	97.04
			σ	0.4	0.00	1	4	17	0.90	10	7	41	1.19	2	1.01
60	20	1976	$\bar{x}$	60.0	21.50	17	26	42	98.19	146	439	4295	19.78	458	97.23
			σ	0.0	3.84	4	6	13	0.12	8	4	26	3.24	12	0.13
60	50	1976	$\bar{x}$	60.4	58.83	22	29	51	97.76	139	447	4361	17.07	447	95.84
			σ	0.8	7.70	1	1	11	0.34	7	4	72	0.26	5	1.41
80	0	1976	$\bar{x}$	80.5	0.00	21	29	48	98.02	146	456	4294	18.70	451	97.06
			σ	0.5	0.00	3	2	19	0.09	12	2	35	1.30	10	0.10
80	0	1977	$\bar{x}$	78.2	0.00	15	26	31	98.25	154	444	4220	17.23	468	97.41
			σ	0.7	0.00	1	4	8	0.71	4	14	7	0.75	2	0.71
80	20	1976	$\bar{x}$	79.7	27.17	20	29	43	98.00	158	449	4242	18.15	471	96.89
			σ	1.2	4.72	3	4	2	0.14	1	3	42	0.54	6	0.14
80	20	1977	$\bar{x}$	77.9	32.75	17	25	46	97.51	153	446	4225	17.81	475	96.66
			σ	0.1	2.92	4	3	4	0.22	1	7	16	0.61	7	0.23
80	50	1976	$\bar{x}$	79.1	45.07	19	29	39	97.92	152	455	4184	18.38	464	96.99
			σ	1.1	5.01	3	5	15	0.50	10	4	26	1.64	10	0.53
80	50	1977	$\bar{x}$	77.7	48.52	31	22	45	97.92	153	443	4227	17.98	476	97.09
			σ	3.2	9.88	8	8	15	0.26	1	9	10	0.48	2	0.26
100	0	1976	$\bar{x}$	96.1	0.00	21	27	60	98.30	151	447	4329	17.43	470	97.34
			σ	2.6	0.00	2	3	15	0.18	9	8	21	0.73	2	0.17
100	20	1976	$\bar{x}$	95.1	25.60	19	29	39	98.14	149	442	4304	18.26	468	97.18
			σ	2.7	4.40	1	3	18	0.60	14	11	30	0.08	6	0.59
100	50	1976	$\bar{x}$	94.7	42.60	22	26	71	97.60	155	468	4321	18.65	471	96.68
			σ	3.0	2.40	4	3	7	0.77	17	17	25	0.74	2	0.76

[a] Re 43,130 kg/h steam.

[b] $\bar{x}$ and σ represent the mean and ± the standard deviation, respectively.

TABLE 34. AVERAGE AIR, FEEDWATER, AND STEAM CHARACTERISTICS FOR EXPERIMENTAL RUNS ON BOILER UNIT 6 (1976-1977)

Nominal						Air temp.					Steam		Flue gas (stack)		
Load (%)	RDF (%)	Year		Steam load[a] (%)	RDF Heat input (%)	Wet bulb (°C)	Dry bulb (°C)	Rel. hum. (%)	Baro. press. (kPa)	Feed-water temp. (°C)	Temp. (°C)	Press. (kPa)	Flow (m^3/s)	Temp. (°C)	Press. (kPa)
60	0	1977	$\bar{x}$ [b]	61.1	0.00	16	23	46	98.31	163	444	4213	18.79	420	97.46
			σ	1.2	0.00	2	2	18	0.20	1	3	28	1.70	2	0.21
60	20	1977	$\bar{x}$	59.6	32.85	17	24	52	98.00	165	442	4206	21.26	429	97.23
			σ	0.4	5.28	4	2	24	0.30	1	1	0	0.99	2	0.23
60	50	1977	$\bar{x}$	60.6	63.43	17	27	37	97.93	163	446	4240	21.73	430	97.13
			σ	3.0	11.16	1	3	16	0.47	2	2	35	2.15	1	0.47
80	0	1976	$\bar{x}$	80.3	0.00	20	25	62	98.29	168	446	4554	19.30	462	97.34
			σ	1.0	0.00	5	5	11	0.36	1	1	49	2.86	1	0.36
80	0	1977	$\bar{x}$	84.0	0.00	14	21	53	98.10	175	446	4185	17.52	464	97.24
			σ	0.8	0.00	0	4	24	0.07	2	4	0	0.70	1	0.08
80	20	1976	$\bar{x}$	80.4	20.73	24	30	65	97.93	167	447	4566	24.38	454	96.98
			σ	1.1	1.08	1	1	4	0.15	0	2	18	1.20	2	0.15
80	50	1976	$\bar{x}$	78.9	44.87	21	28	54	97.90	167	445	4577	21.44	473	96.92
			σ	0.5	11.48	2	4	10	0.39	1	1	49	0.33	5	0.38
80	50	1977	$\bar{x}$	86.0	46.15	24	27	56	97.66	175	442	4302	20.25	475	96.82
			σ	23.0	7.78	2	0	14	0.20	0	0	28	0.04	0	0.19

[a] Re 56,750 kg/h steam.

[b] $\bar{x}$ and σ represent the mean and ± the standard deviation, respectively.

TABLE 35. MEAN VALUES OF COAL AND RDF CHARACTERISTICS

Quantity	RDF	Iowa coal	Iowa-Wyoming coal[a]
Number of samples	39	28	32
Heating value (HHV)	13.41 MJ/kg (5757 Btu/lb)	21.85 MJ/kg (9393 Btu/lb)	22.14 MJ/kg (9500 Btu/lb)
Moisture(%)	19.77%	10.85%	16.65%
Ash(%)	15.16	20.24	11.73
Carbon(%)	31.62	51.71	54.32
Hydrogen(%)	4.65	3.96	2.86
Sulfur(%)	0.40	6.66	3.06
Chlorine(%)	0.28	0.04	0.05
Oxygen(%)	28.12	6.54	11.33
Total(%)	100.00	100.00	100.00
Trace elements[b]			
Al (%)	1.16	1.46	1.25
Si (%)	2.79	2.50	2.17
K (%)	0.28	0.12	0.11
Ca (%)	1.95	1.76	1.12
Fe (%)	0.47	2.17	1.59
Ti	1903	518	689
V	161	33.4	67.4
Cr	38.9	24.0	21.9
Mn	218	116	83.9
Ni	13.9	11.6	14.3
Cu	211	17.5	19.5
Zn	876	35.6	87.8
Gd	20.9	2.48	2.89
Ge	1.37	8.87	6.30
As	0.84	5.08	5.63
Se	0.58	2.00	8.34
Rb	8.33	4.85	4.41
Sr	64.4	24.0	86.3
Pb	1256	96.6	51.7

[a] The Iowa-Wyoming coal is a 50-50 mixture.

[b] Units are in parts per million (ppm) by weight unless otherwise noted.

TABLE 36. ANALYSIS OF BOTTOM ASH AND HOPPER ASH[a] FROM BOILER UNIT 5 (1976-1977)

Parameter (units)	80% load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF	80% load 1977 Iowa-Wyoming coal with 0% RDF	 20% RDF	 50% RDF
Mineral ash (%)	87.60 (84.44)	82.43 (88.29)	90.15 (88.85)	91.95 (78.55)	93.08 (88.32)	90.00 (90.52)
Carbon (%)	8.81 (12.89)	13.01 (7.61)	6.84 (8.14)	6.07 (19.39)	5.53 (9.99)	8.04 (7.73)
Hydrogen (%)	0.67 (0.61)	0.92 (0.43)	0.77 (0.67)	0.17 (0.25)	0.21 (0.14)	0.28 (0.14)
Sulfur (%)	2.92 (1.98)	3.54 (3.66)	2.24 (2.33)	1.79 (1.80)	1.17 (1.51)	1.65 (1.58)
Chlorine (%)	--- ---	--- ---	--- ---	0.02 (0.00)	0.02 (0.03)	0.04 (0.03)

Parameter (units)	60% load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF	100% load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF
Mineral ash (%)	87.06 (84.71)	88.46 (89.57)	89.77 (95.10)	86.91 (79.47)	85.96 (88.10)	85.04 (88.06)
Carbon (%)	8.59 (12.83)	7.50 (7.70)	7.01 (3.37)	9.44 (17.97)	9.64 (8.74)	11.16 (8.60)
Hydrogen (%)	0.87 (0.65)	0.86 (0.60)	0.90 (0.51)	0.77 (0.53)	0.63 (0.56)	0.70 (0.81)
Sulfur (%)	3.49 (1.82)	3.18 (2.14)	2.31 (1.03)	2.87 (2.04)	3.75 (2.61)	3.12 (2.53)

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[a] Items in parentheses are for hopper ash.

TABLE 37. ANALYSIS OF BOTTOM ASH AND HOPPER ASH[a] FROM BOILER UNIT 6 (1976-1977)

Parameter (units)	80% load 1976 Iowa-Wyoming coal with 0% RDF		20% RDF		50% RDF		80% load 1977 Iowa-Wyoming coal with 0% RDF		50% RDF	
Mineral ash (%)	93.48	(84.75)	94.79	(87.97)	96.09	(87.19)	93.86	(81.87)	96.06	(91.79)
Carbon (%)	3.77	(12.93)	2.84	(9.51)	2.31	(10.17)	4.30	(16.59)	2.74	(6.95)
Hydrogen (%)	0.81	(0.64)	0.71	(0.58)	0.51	(0.85)	0.23	(0.21)	0.19	(0.18)
Sulfur (%)	1.95	(1.68)	1.65	(1.94)	1.09	(1.79)	1.58	(1.33)	0.99	(1.07)
Chlorine (%)	---	---	---	---	---	---	0.04	(0.01)	0.03	(0.03)

Parameter (units)	60% load 1977 Iowa-Wyoming coal with 0% RDF		20% RDF		50% RDF	
Mineral ash (%)	96.76	(85.48)	96.72	(91.84)	96.78	(84.23)
Carbon (%)	2.04	(12.48)	2.23	(6.49)	2.32	(4.45)
Hydrogen (%)	0.13	(0.23)	0.12	(0.17)	0.16	(0.13)
Sulfur (%)	1.06	(1.76)	0.90	(1.48)	0.71	(1.03)
Chlorine (%)	0.01	(0.02)	0.03	(0.02)	0.02	(0.06)

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[a] Items in parentheses are for hopper ash.

TABLE 38. SELECTED EMISSIONS FROM BOILER UNIT 5 (1976-1977)

Parameter (units)		80% load 1976 Iowa coal with			80% load 1977 Iowa-Wyoming coal with		
		0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
Particulates (controlled)	(g/MJ)	0.7 ± 0.5	0.4 ± 0.0	0.3 ± 0.1	0.8 ± 0.2	0.9 ± 0.1	1.0 ± 0.2
Particulates (uncontrolled)	(g/MJ)	3.6 ± 0.6	4.1 ± 0.2	3.4 ± 0.2	3.2 ± 0.5	3.8 ± 0.3	4.2 ± 0.9
Oxides of sulfur, SO_x	(g/MJ)	2.3 ± 0.0	1.9 ± 0.2	1.5 ± 0.6	1.0 ± 0.3	0.7 ± 0.2	0.9 ± 0.4
Oxides of nitrogen, NO_x	(mg/MJ)	80.0 ±25.0	76.0 ±10.0	64.0 ±17.0	77.0 ± 6.0	67.0 ± 6.0	69.0 ±13.0
Chlorides	(mg/MJ)	13.0 ± 3.0	68.0 ± 8.0	97.0 ±43.0	6.5 ± 0.7	87.0 ±21.0	139.0 ±42.0
Formaldeyhde	(mg/MJ)	0.2 ± 0.3	0.2 ± 0.1	4.3 ± 4.1	11.7 ±18.2	3.7 ± 1.9	3.4 ± 3.1
Hydrocarbons	(mg/MJ)	0.22± 0.13	0.17± 0.07	0.19± 0.08	0.08± 0.06	0.09± 0.04	0.07± 0.03

Parameter (units)		60% load 1976 Iowa coal with			100% load 1976 Iowa coal with		
		0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF[a/]
Particulates (controlled)	(g/MJ)	0.9 ± 0.5	1.1 ± 0.6	1.3 ± 0.7	1.3 ± 0.9	0.4 ± 0.1	0.4 ± 0.1
Particulates (uncontrolled)	(g/MJ)	3.2 ± 0.5	4.4 ± 0.6	3.5 ± 1.4	4.1 ± 1.1	2.2 ± 0.8	3.1 ± 1.3
Oxides of sulfur, SO_x	(g/MJ)	1.3 ± 1.0	2.3 ± 0.5	0.8 ± 0.4	2.4 ± 0.0	2.0 ± 0.3	1.7 ± 0.3
Oxides of nitrogen, NO_x	(mg/MJ)	99.0 ±12.0	104.0 ± 8.0	78.0 ±20.0	81.0 ±17.0	76.0 ±17.0	50.0 ± 8.0
Chlorides	(mg/MJ)	22.0 ±12.0	58.0 ±17.0	100.0 ±55.0	7.0 ± 0.0	62.0 ±22.0	101.0 ±21.0
Formaldehyde	(mg/MJ)	2.7 ± 2.7	3.1 ± 3.3	6.2 ± 8.1	3.3 ± 3.6	2.0 ± 2.8	0.2 ± 0.1
Hydrocarbons	(mg/MJ)	0.15± 0.08	0.19± 0.08	0.31± 0.12	0.09± 0.06	0.15± 0.06	0.17± 0.01

[a/] Only two runs at this load and % RDF were accomplished.

TABLE 39. SELECTED EMISSIONS FROM BOILER UNIT 6

Parameter (units)		80% load 1976 Iowa-Wyoming coal with			80% load 1977 Iowa-Wyoming coal with	
		0% RDF	20% RDF	50% RDF	0% RDF[a]	50% RDF[a]
Particulates (controlled)	(g/MJ)	0.5±0.1	0.7±0.2	0.9± 0.1	0.8 ±0.1	1.9 ± 0.1
Particulates (uncontrolled)	(g/MJ)	2.5±0.7	3.5±0.3	4.4± 0.9	1.8 ±0.3	3.9 ± 0.2
Oxides of sulfur, SO_x	(g/MJ)	0.8±0.5	0.3±0.0	0.4± 0.4	0.9 ±0.1	0.6 ± 0.1
Oxides of nitrogen, NO_x	(mg/MJ)	133.0±6.0	131.0±5.0	106.0± 3.0	91.0 ±6.0	88.0 ± 5.0
Chlorides	(mg/MJ)	6.3±3.2	44.0±5.0	88.0±33.0	9.4 ±1.5	110.0 ±15.0
Formaldehyde	(mg/MJ)	5.8±9.0	0.6±0.1	1.6± 0.1	16.0 ±5.0	20.0 ± 8.0
Hydrocarbons	(mg/MJ)	---	---	---	0.07±0.00	0.13± 0.06

Parameter (units)		60% load 1977 Iowa-Wyoming coal with		
		0% RDF	20% RDF	50%RDF
Particulates (controlled)	(g/MJ)	0.7 ± 0.1	1.8 ± 0.4	1.7 ± 0.2
Particulates (uncontrolled)	(g/MJ)	2.0 ± 0.4	3.7 ± 0.4	4.3 ± 0.3
Oxides of sulfur, SO_x	(g/MJ)	1.4 ± 0.2	0.8 ± 0.1	0.5 ± 0.0
Oxides of nitrogen, NO_x	(mg/MJ)	106.0 ±11.0	52.0 ±10.0	96.0 ± 4.0
Chlorides	(mg/MJ)	4.2 ± 1.1	96.0 ±12.0	127.0 ±32.0
Formaldehyde	(mg/MJ)	22.0 ±12.0	28.0 ± 7.0	23.0 ±17.0
Hydrocarbons	(mg/MJ)	0.08± 0.04	0.07± 0.00	0.07± 0.01

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[a] Only two runs at this load and % RDF were accomplished.

Each data point, except where noted, represents the average of three independent test runs. The standard deviations are the variations caused by uncontrolled factors in the experiment and the experimental measurement uncertainty. The data are plotted to show the trends of the emissions with increases in RDF. Tables 40 and 41 include the average amount of trace elements detected in the bottom ash and fly ash from boiler units 5 and 6, respectively. Tables 42 through 45 are tabulations of trace elements detected on the particulate filter and from the impinger solution, respectively, from the EPA Method 5 sampling train.

Particulate--

Figures 39 and 40 show uncontrolled particulate emissions from units 5 and 6. The uncontrolled particulate emissions from unit 5 have no discernible trend within the data scatter for 1976. However, the data taken during 1977 indicate a nearly linear increase in emissions of about 30% from 0% RDF to 50% RDF at a boiler load of 80%. This trend is similar to that indicated for unit 6, but the effect is much less exaggerated in unit 5. At 100% load, unit 5 was not stable in operation when the amount of RDF was increased to 50% which may account for considerable uncertainty in the data at this operating condition. The scatter in the 1976 data also reflects changes in uncontrolled factors in the tests while the operators were learning how to run the boilers when burning RDF with coal.

Uncontrolled particulate emissions from unit 6 increase about 100% in a nearly linear fashion from 0% RDF to 50% at boiler loads of both 60% and 80%. The trends for the data for 1976 are similar to those of the data for 1977. However, at 80% load, the magnitude of the uncontrolled particulate emissions on unit 6 was about one-third higher during 1976 than during 1977. In large part, this may reflect the learning experience of the boiler operators in controlling the amount of additional air routed to the boiler for burning the fuel. Increased air flow through the boiler appears to help carry proportionately more fine particulates through the boiler passages to the particulate collectors.

The increase in uncontrolled particulates with increased in RDF is believed to be due to the additional amount of air routed into the stoker-fired boilers in order to properly burn the RDF and to maintain a proper firebed on the boiler grates. The air flow through the boiler appears to carry additional particulate matter (fly ash) through the boiler passages in nearly direct proportion to the amount of the increase in air with RDF. The effect on unit 6 is exaggerated because its physical size in cross section is about the same as unit 5. However, boiler 6 generates 12 MW, while boiler 5 generates 7.5 MW. Thus, the air flow through boiler 6 is significantly larger than that through boiler 5.

TABLE 40. TRACE ELEMEMENT ANALYSIS OF BOTTOM ASH AND HOPPER ASH[a] FROM BOILER UNIT 5 (1976-1977)

Parameter (ppm except where noted)	80% load 1976 Iowa coal with			80% load 1977 Iowa coal with		
	0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
Al (%)	5.0 (5.6)	3.1 (4.4)	3.4 (5.2)	7.9 (5.9)	5.0 (6.2)	4.5 (5.9)
Si (%)	9.6 (12.7)	7.1 (10.8)	11.1 (13.7)	14.3 (10.7)	15.4 (14.5)	14.5 (14.6)
K (%)	0.52 (1.10)	0.52 (1.04)	0.63 (1.23)	0.91 (0.99)	0.84 (1.28)	0.82 (1.21)
Ca (%)	14.0 (10.4)	9.2 (10.0)	7.9 (9.0)	7.4 (7.4)	7.9 (9.1)	7.5 (9.4)
Fe (%)	12.6 (13.3)	12.9 (8.5)	11.0 (6.9)	14.6 (12.7)	8.6 (5.9)	8.7 (5.4)
Ti (%)	0.31 (0.40)	<0.20 (<0.42)[b]	<0.32 (<0.65)	0.53 (0.49)	0.50 (0.75)	0.51 (0.73)
V	317 (<413)	<363 (<840)	<503 (<987)	823 (<773)	790 (<767)	743 (<750)
Cr	257 (156)	247 (200)	297 (228)	207 (233)	270 (173)	245 (171)
Mn	987 (717)	1050 (1143)	990 (1190)	870 (820)	840 (1097)	863 (1165)
Ni	34.7 (47.0)	45.0 (40.0)	48.0 (64.7)	57.7 (53.3)	38.3 (560)	52.3 (50.3)
Cu	48.0 (63.3)	457 (150)	393 (203)	73.7 (71.0)	783 (202)	618 (198)
Zn	318 (730)	347 (1867)	600 (3230)	1323 (660)	900 (2270)	1013 (2415)
Ga	<10 (<23.7)	16.3 (<59.0)	21.0 (<73.0)	24.7 (<22.0)	27.3 (<68.7)	28.3 (<70.0)
Ge	<8.3 (37.7)	12.3 (48.7)	10.3 (34.7)	28.0 (18.7)	12.7 (17.7)	10.8 (21.0)
As	<10 (<10)	--- (<10)	<10 (<10)	<10 (<10)	<10 (<10)	<10 (<10)
Se	<5 (<5)	<5 (<5)	<5 (<5)	<5 (<5)	<5 (<5)	<5 (<5)
Rb	31.0 (43.7)	26.3 (34.7)	29.3 (38.0)	42.7 (44.0)	39.0 (34.3)	38.0 (30.0)
Sr	133 (168)	157 (287)	180 (300)	510 (558)	362 (453)	345 (444)
Pb	55.0 (557)	355 (1447)	413 (1890)	101 (332)	363 (1927)	483 (1845)

(continued)

TABLE 40. (concluded)

Parameter (ppm except where noted)	60% load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF	100 % load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF
Al (%)	4.12 (6.72)	2.98 (5.83)	4.03 (6.70)	3.87 (5.83)	3.87 (4.83)	3.40 (4.50)
Si (%)	8.68 (13.2)	8.75 (13.1)	13.0 (16.6)	8.97 (12.2)	9.70 (11.4)	11.1 (11.9)
K (%)	0.74 (1.15)	0.63 (1.15)	0.85 (1.44)	0.70 (1.02)	0.70 (1.04)	0.71 (1.00)
Ca (%)	12.6 (11.7)	12.4 (10.6)	11.2 (10.7)	11.2 (9.80)	11.1 (10.5)	10.4 (10.8)
Fe (%)	10.6 (13.4)	7.58 (6.63)	6.25 (5.14)	14.8 (9.23)	10.6 (8.63)	11.1 (9.05)
Ti (%)	<0.26 (<0.43)	<0.19 (<0.47)	<0.44 (<0.75)	<0.22 (<0.32)	<0.28 (<0.48)	<0.32 (<0.50)
V	336 (<512)	349 (<810)	613 (<835)	263 (<573)	368 (<690)	373 (<588)
Cr	364 (156)	373 (203)	437 (190)	597 (175)	250 (207)	298 (263)
Mn	1030 (833)	1168 (1080)	987 (1290)	1183 (875)	1050 (997)	928 (1000)
Ni	55.4 (42.4)	53.0 (45.0)	116 (47.0)	112 (43.0)	38.0 (58.0)	32.0 (41.5)
Cu	118 (57.4)	379 (122)	820 (253)	421 (48.3)	248 (137)	418 (248)
Zn	181 (583)	258 (1490)	820 (2460)	420 (398)	427 (1620)	455 (1250)
Ga	9.80 (24.8)	11.3 (39.7)	23.0 (54.0)	6.33 (20.0)	<17.7 (<46.7)	<15.0 (<38.5)
Ge	8.40 (42.0)	9.75 (35.0)	8.67 (17.0)	6.67 (36.7)	14.0 (45.3)	9.50 (27.0)
As	<10 (<10)	<10 (<10)	<10 (<10)	<10 (<10)	<10 (<10)	<10 (<10)
Se	<5 (<3.8)	<5 (<5)	<5 (<5)	<5 (<5)	<5 (<5)	<5 (<5)
Rb	26.2 (41.0)	24.3 (39.0)	26.0 (32.0)	29.3 (45.7)	25.3 (33.7)	26.5 (32.0)
Sr	197 (292)	138 (233)	150 (287)	150 (183)	157 (227)	165 (220)
Pb	97.4 (581)	198 (830)	487 (1360)	81.7 (347)	342 (1190)	285 (850)

[a/] Hopper ash values are in parentheses.

[b/] The symbol < indicates element may be present but in quantities less than indicated value.

TABLE 41. TRACE ELEMENT ANALYSIS OF BOTTOM ASH AND HOPPER ASH[a] FROM BOILER UNIT 6 (1976-1977)

Parameter (ppm except where noted)	80% load 1976 Iowa/Wyoming coal with 0% RDF	 20% RDF	 50% RDF	80% load 1977 Iowa coal with 0% RDF	 50% RDF
Al (%)	6.07 (5.80)	5.63 (6.10)	5.0 (6.23)	9.20 (7.86)	6.80 (7.15)
Si (%)	13.9 (12.4)	15.3 (12.7)	18.1 (13.8)	15.4 (13.1)	17.1 (15.7)
K (%)	0.91 (1.07)	0.88 (1.23)	0.9 (1.33)	1.28 (1.18)	1.03 (1.37)
Ca (%)	11.7 (11.4)	11.4 (11.4)	10.9 (11.8)	6.68 (7.33)	7.79 (9.66)
Fe (%)	13.4 (10.8)	10.5 (8.65)	6.32 (7.57)	11.4 (10.3)	6.39 (6.11)
Ti (%)	<0.40 (<0.5)[b]	<0.43 (<0.63)	<0.43 (<0.73)	0.47 (0.48)	0.52 (0.73)
V	<527 (<970)	<527 (<817)	<553 (<950)	<745 (<870)	<800 (<760)
Cr	307 (137)	330 (150)	307 (153)	260 (150)	340 (205)
Mn	877 (783)	757 (953)	763 (1100)	775 (725)	475 (1310)
Ni	52.3 (47.3)	57.7 (51.7)	54.7 (51.3)	72.5 (87.5)	62.5 (67.0)
Cu	132 (82.0)	607 (139)	1030 (171)	90.0 (98.0)	300 (190)
Zn	197 (733)	450 (1610)	1080 (2090)	445 (760)	708 (2140)
Ga	11.0 (<26.0)	16.0 (<43.3)	<37.0 (<49.7)	18.5 (<27.5)	<27.0 (57.5)
Ge	<7.0 (30.0)	<8.67 (32.7)	<25.3 (28.3)	<10 (22.0)	<10 (13.5)
As	<10.0 (<10.0)	<10 (<10)	<10 (<10)	<10 (<10)	<10 (<10)
Se	<5.0 (<5.0)	<5 (<5)	<5 (<5)	<5 (<5)	<5 (<5)
Rb	35.0 (34.3)	32.7 (36.7)	37.7 (37.7)	70.5 (54.5)	55.5 (44.0)
Sr	553 (787)	437 (615)	437 (693)	460 (773)	415 (595)
Pb	55.0 (467)	257 (950)	937 (1130)	47.0 (420)	540 (1520)

(continued)

TABLE 41. (concluded)

Parameter (ppm except where noted)	60% load 1977 Iowa/Wyoming coal with 0% RDF	 20% RDF	 50% RDF
Al (%)	6.50 (8.47)	5.30 (6.75)	4.57 (6.50)
Si (%)	13.8 (14.0)	17.5 (14.8)	19.5 (17.3)
K (%)	0.92 (1.08)	0.84 (1.18)	0.86 (1.49)
Ca (%)	7.86 (7.50)	8.41 (9.38)	9.62 (9.93)
Fe (%)	16.0 (12.2)	7.48 (7.85)	4.70 (4.97)
Ti (%)	0.47 (0.46)	0.57 (0.64)	0.62 (0.87)
V	<667 (<763)	<530 (<668)	<697 (<727)
Cr	247 (170)	435 (163)	307 (208)
Mn	950 (713)	805 (1050)	822 (1540)
Ni	54.0 (61.0)	<29.0 (59.3)	49.0 (63.0)
Cu	60.0 (60.3)	1830 (139)	653 (223)
Zn	967 (857)	1110 (1740)	1240 (3320)
Ga	16.0 (24.0)	<27.3 (<47.3)	<35.7 (<76.3)
Ge	<10.0 (26.3)	<10.0 (17.3)	<10.0 (15.0)
As	<10.0 (<10.0)	<10.0 (<10.0)	<10.0 (<10.0)
Se	<5.0 (<5.0)	<5.0 (<5.0)	<5.0 (<5.0)
Rb	47.3 (50.0)	39.3 (33.5)	55.3 (<30.3)
Sr	420 (603)	400 (475)	366 (433)
Pb	<90.0 (343)	522 (1180)	1850 (2220)

[a] Hopper ash values are in parentheses.

[b] The symbol < indicates element may be present but in quantities less than indicated value.

TABLE 42. TRACE ELEMENT ANALYSIS OF PARTICULATES ON PARTICULATE SAMPLE TRAIN FILTERS FROM BOILER UNIT 5 (1976-1977)

Parameter (mg/MJ)	80% Load 1976 Iowa coal with			80% Load 1977 Iowa-Wyoming coal with		
	0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
Al	8.00	10.7	14.6	7.67	8.73	10.0
S	17.40	35.2	20.4	15.30	11.80	11.3
K	0.987	2.56	2.63	1.67	4.38	4.47
Ca	12.49	3.03	1.90	5.33	6.51	6.00
Fe	1.29	5.00	3.47	8.91	5.11	3.79
Ti	0.424	0.635	0.598	0.597	1.23	1.31
V	0.893	0.095	0.095	0.094	0.153	0.145
Cr	0.032	0.033	0.030	0.018	0.055	0.040
Mn	0.093	0.067	0.066	0.075	0.110	0.102
Ni	0.027	0.015	0.018	0.026	0.022	0.017
Cu	0.029	0.066	0.071	0.027	0.085	0.077
Zn	2.44	4.68	5.81	1.20	5.35	5.55
Ga	0.064	0.204	0.152	0.037	0.186	0.199
Ge	0.236	0.121	0.074	0.074	0.061	0.048
As	0.00	0.00	0.00	0.023	0.032	0.037
Se	0.013	0.016	0.019	0.007	0.011	0.021
Rb	0.00	0.00	0.00	0.013	0.027	0.073
Sr	0.00	0.00	0.00	505.000	521.000	551.000
Pb	1.28	6.80	4.73	0.128	0.084	0.062

(continued)

TABLE 42 (concluded)

Parameter (mg/MJ)	60% Load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF	100% Load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF
Al	31.1	24.5	38.1	19.3	13.4	14.1
S	66.4	31.5	30.0	25.1	45.3	38.2
K	3.86	3.45	1.12	2.74	6.76	3.92
Ca	11.2	7.74	10.9	9.04	4.88	5.29
Fe	16.6	11.7	8.67	17.6	6.06	4.91
Ti	0.883	1.58	3.27	0.842	0.662	0.953
V	0.115	0.203	0.352	0.128	0.090	0.142
Cr	0.038	0.064	0.098	0.041	0.034	0.033
Mn	0.126	0.115	0.177	0.134	0.085	0.080
Ni	0.029	0.024	0.026	0.0384	0.017	0.014
Cu	0.033	0.052	0.183	0.036	0.093	0.080
Zn	0.828	4.58	12.0	2.05	5.94	6.18
Ga	0.058	0.153	0.247	0.087	0.234	0.182
Ge	0.243	0.230	0.191	0.250	0.170	0.119
As	0.075	0.034	0.058	0.048	0.00	0.00
Se	0.019	0.027	0.035	0.009	0.018	0.021
Rb	0.014	0.008	0.022	0.024	0.005	0.008
Sr	0.043	0.022	0.046	0.072	0.002	0.006
Pb	0.870	4.68	8.78	1.38	4.90	4.92

TABLE 43. TRACE ELEMENT ANALYSIS OF PARTICULATES ON PARTICULATE SAMPLE TRAIN FILTERS FROM BOILER UNIT 6 (1976-1977)

Parameter (mg/MJ)	80% Load 1976 Iowa-Wyoming coal with			80% Load 1977 Iowa-Wyoming coal with	
	0% RDF	20% RDF	50% RDF	0% RDF	50% RDF
Al	6.10	2.04	9.62	12.6	21.3
S	26.9	17.4	18.9	18.5	13.3
K	2.11	3.41	3.80	2.68	5.22
Ca	9.26	8.09	6.47	8.04	8.97
Fe	6.82	3.69	3.15	9.30	5.23
Ti	0.593	1.20	1.49	1.00	2.39
V	0.126	0.181	0.190	0.211	0.394
Cr	0.026	0.044	0.047	0.031	0.127
Mn	0.067	0.091	0.093	0.090	0.187
Ni	0.023	0.016	0.014	0.056	0.039
Cu	0.046	0.079	0.114	0.059	0.142
Zn	0.591	3.58	6.12	1.75	6.94
Ga	0.049	0.131	0.210	0.062	0.196
Ge	0.098	0.046	0.019	0.104	0.064
As	0.049	0.000	0.000	0.063	0.032
Se	0.005	0.016	0.030	0.007	0.010
Rb	0.018	0.011	0.014	0.020	0.133
Sr	0.206	0.181	0.131	0.227	0.131
Pb	0.810	4.95	6.66	1.00	6.01

(continued)

TABLE 43. (concluded)

Parameter (mg/MJ)	60% Load 1977 Iowa-Wyoming coal with 0% RDF	20% RDF	50% RDF
Al	154.0	258.0	166.0
S	132.0	45.5	107.0
K	4.86	14.2	16.0
Ca	12.3	22.7	19.0
Fe	12.9	8.05	6.58
Ti	1.27	3.76	4.29
V	0.199	0.395	0.502
Cr	0.043	0.170	0.161
Mn	0.107	0.219	0.294
Ni	0.048	0.045	0.039
Cu	0.062	0.193	0.217
Zn	3.23	13.5	14.3
Ga	0.065	0.430	0.372
Ge	0.138	0.156	0.083
As	0.104	0.516	0.387
Se	0.071	0.103	0.077
Rb	0.021	0.021	0.032
Sr	0.271	0.145	1.90
Pb	0.497	10.9	8.01

TABLE 44. TRACE ELEMENT ANALYSIS OF IMPINGER WATER FROM PARTICULATE SAMPLE TRAIN ON BOILER UNIT 5 (1976-1977)

Parameter (µg/MJ)	80% Load 1976 Iowa coal with			80% Load 1977 Iowa-Wyoming coal with		
	0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
As	85.6	159.0	252.0	23.67	15.59	6.53
Be	0.082	0.137	0.000	0.013	0.000	0.000
Cd	2.72	4.25	3.27	2.13	0.000	0.271
Co	25.5	7.69	12.5	7.11	1.94	8.72
Cr	0.246	1.67	0.000	0.000	0.000	0.113
Cu	0.568	2.01	0.780	0.186	0.000	0.030
Ga	4.09	8.33	9.36	0.000	0.000	0.000
Ge	9.01	10.8	0.000	0.000	0.000	0.000
Hg	11.5	28.3	---	0.000	0.924	3.60
Mn	0.207	0.482	0.057	0.000	0.000	0.000
Ni	1.64	3.33	46.8	0.000	0.000	0.000
Pb	25.4	21.1	10.4	0.000	0.000	1.00
Sb	33.7	41.6	62.4	0.000	0.000	1.87
Se	49.0	83.5	127.0	8.74	0.000	19.51
Sn	60.4	143.0	93.6	0.000	0.000	0.000
Sr	1.64	4.16	0.000	0.000	0.000	0.000
V	0.491	0.833	0.000	0.000	0.000	0.000
Zn	0.049	4.03	0.000	2.33	3.43	3.42

(continued)

TABLE 44. (concluded)

Parameter (μg/MJ)	60% Load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF	100% Load 1976 Iowa coal with 0% RDF	 20% RDF	 50% RDF
As	546.0	407.0	117.0	30.5	157.0	188.0
Be	0.026	0.042	0.116	0.061	0.159	0.147
Cd	6.98	3.23	0.218	2.08	2.95	1.36
Co	7.58	4.21	24.7	3.47	3.48	0.000
Cr	0.129	0.421	0.449	0.196	1.39	0.000
Cu	2.85	0.063	0.278	1.00	4.87	0.735
Ga	0.582	1.89	2.02	0.777	6.95	0.000
Ge	115.0	4.21	4.49	1.96	13.2	0.000
Hg	5.17	16.8	18.0	11.8	23.6	---
Mn	0.291	1.19	0.064	0.010	0.736	0.000
Ni	0.517	1.68	1.80	15.3	2.78	0.000
Pb	118.0	8.94	2.85	12.6	25.0	0.000
Sb	134.0	18.9	2.25	16.5	56.8	0.000
Se	256.0	203.0	53.8	26.2	69.9	84.3
Sn	244.0	273.0	869.0	34.5	303.0	176.0
Sr	0.646	2.10	2.25	0.982	4.17	0.000
V	0.065	0.210	0.225	0.098	1.39	0.000
Zn	0.039	0.126	2.52	0.059	2.09	0.000

TABLE 45. TRACE ELEMENT ANALYSIS OF IMPINGER WATER FROM PARTICULATE SAMPLE TRAIN ON BOILER UNIT 6 (1976-1977)

Parameter (µg/MJ)	80% Load 1976 Iowa-Wyoming Coal with 0% RDF	20% RDF	50% RDF	80% Load 1977 Iowa-Wyoming Coal with 0% RDF	50% RDF	60% Load 1977 Iowa-Wyoming Coal with 0% RDF	20% RDF	50% RDF
As	38.6	---	12.7	10.1	15.7	23.3	55.2	2.93
Be	0.064	0.000	0.042	0.062	0.000	0.115	0.267	0.049
Cd	1.61	1.37	1.52	0.689	0.236	1.25	0.675	0.143
Co	3.17	3.94	9.71	0.395	0.000	0.000	2.95	3.73
Cr	0.186	0.000	0.085	0.000	0.000	0.000	0.000	0.000
Cu	0.631	0.355	0.604	0.204	0.130	0.000	0.000	0.000
Ga	0.709	0.000	0.382	4.58	0.000	0.646	0.000	0.000
Ge	28.1	78.8	60.9	0.000	0.000	0.000	0.000	0.000
Hg	7.44	0.000	3.40	9.12	0.000	2.37	24.0	24.2
Mn	0.140	0.000	0.152	0.191	0.242	0.026	0.000	0.000
Ni	26.9	0.000	29.9	5.09	4.09	6.40	0.000	5.78
Pb	29.9	78.8	60.4	3.12	4.47	5.00	9.28	0.000
Sb	31.5	61.7	70.4	2.48	0.000	2.10	3.37	0.000
Se	52.1	105.0	132.0	3.06	9.29	32.8	58.7	15.5
Sn	80.6	258.0	220.0	150.0	160.0	39.0	138.0	860.0
Sr	0.929	0.000	5.35	0.000	0.000	0.000	0.000	0.000
V	0.093	0.000	0.043	0.150	0.000	0.000	0.000	0.000
Zn	0.056	0.000	0.026	3.07	2.95	1.87	3.22	5.60

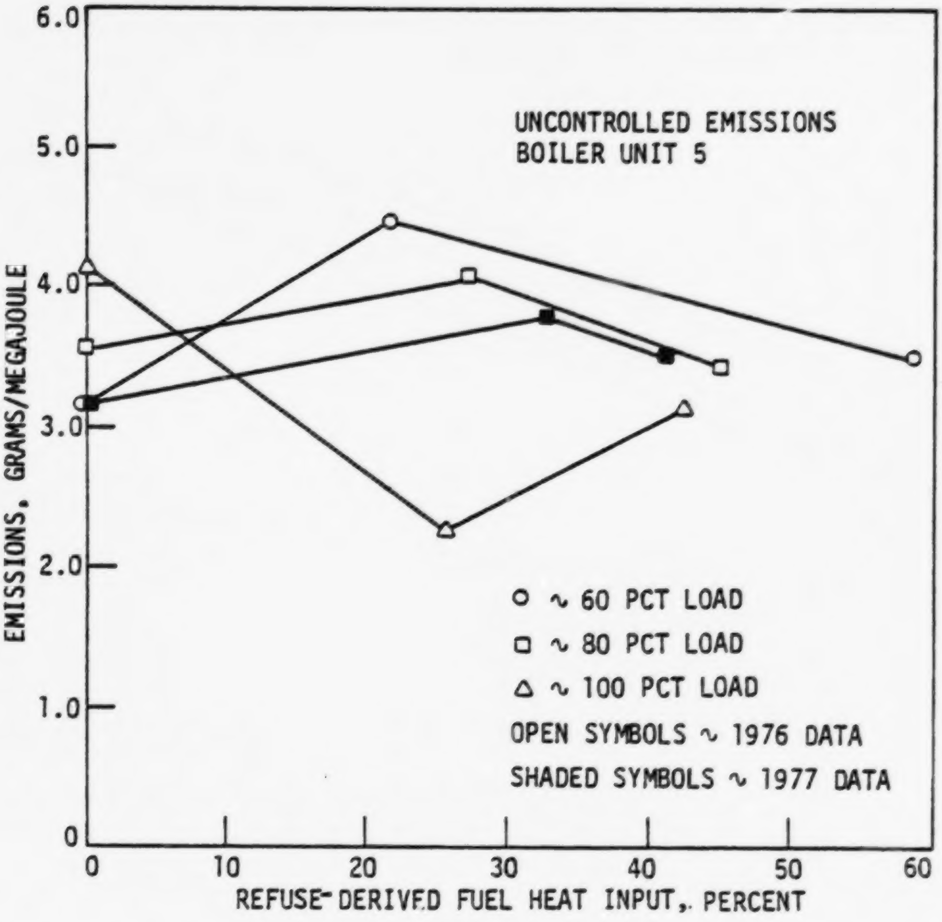

Figure 39. Uncontrolled emissions from stoker-fired boiler unit 5.

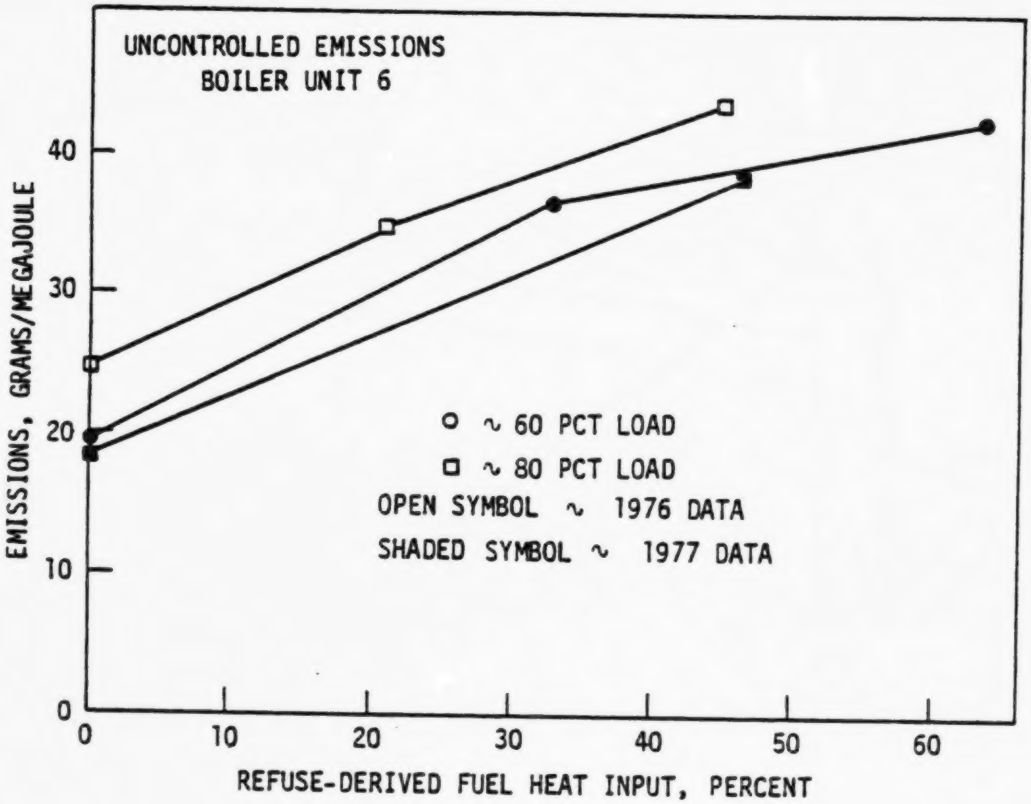

Figure 40. Uncontrolled particulate emissions from stoker-fired boiler unit 6.

The controlled particulate emissions from unit 5 and 6 are shown in Figures 41 and 42, respectively. For unit 6 the trend in controlled emissions is quite similar to the trend in uncontrolled emissions. The efficiency of the multiclone particulate collector on this boiler changed a few percentage points depending on boiler load and percentage RDF. However, the relatively large changes in uncontrolled particulate emissions with percentage RDF were far more significant in affecting the controlled emissions than were the slight changes in collector efficiency. The particulate collector efficiencies are given in Figures 43 and 44 for units 5 and 6 respectively.

The controlled particulate emissions from unit 5 increase in some cases and decrease in others as can be observed in Figure 41. At 80% and 100% load, the particulate emissions dropped with increases in percentage RDF during the 1976 experimental runs. However, the 80% load data for the 1977 experimental runs indicate an increase in particulate emissions with percentage RDF similar to the 60% load data of 1976. This trend is also similar to all of the unit 6 particulate emissions, but the magnitude is significantly less. The reason for the reversal of trends with unit 5 is not known, but it may be related to the new experience of firing RDF with coal in the stoker-fired boilers. Unit 5 was the first unit used and tested in this regard. Thus, the data scatter and uncertainty are larger on unit 5 than on unit 6 because of the larger variability in uncontrolled factors of the boiler operation for 1976 tests.

The particulates, when burning RDF, are both lighter in weight and bigger in size. These factors, in addition to the increased air flow, contribute to the ability of the particulates to be carried out of the boiler when burning RDF as a portion of the input fuel. Figures 45 and 46 show the typical relative changes in size distribution as RDF is increased in units 5 and 6, respectively, at boiler loads of 80%.

Figure 47 is a plot of the particulate emissions with ash content of the fuel for boiler unit 6. This figure indicates that unit 6 will probably not meet compliance regulations unless a very low ash fuel is used or unless the particulate collector is replaced. The additional air flow through this boiler, as previously mentioned, is believed to be the cause of the particulate carry-over.

Another interesting observation from these experiments is that fouling of the slag screen and superheater section of unit 5 was experienced while burning RDF. After the slag screen and superheater were cleaned, the emissions from the boiler increased significantly. The current cleaning and maintenance schedule has kept the slag screen and superheater section of the boiler relatively clean since that initial fouling experience.

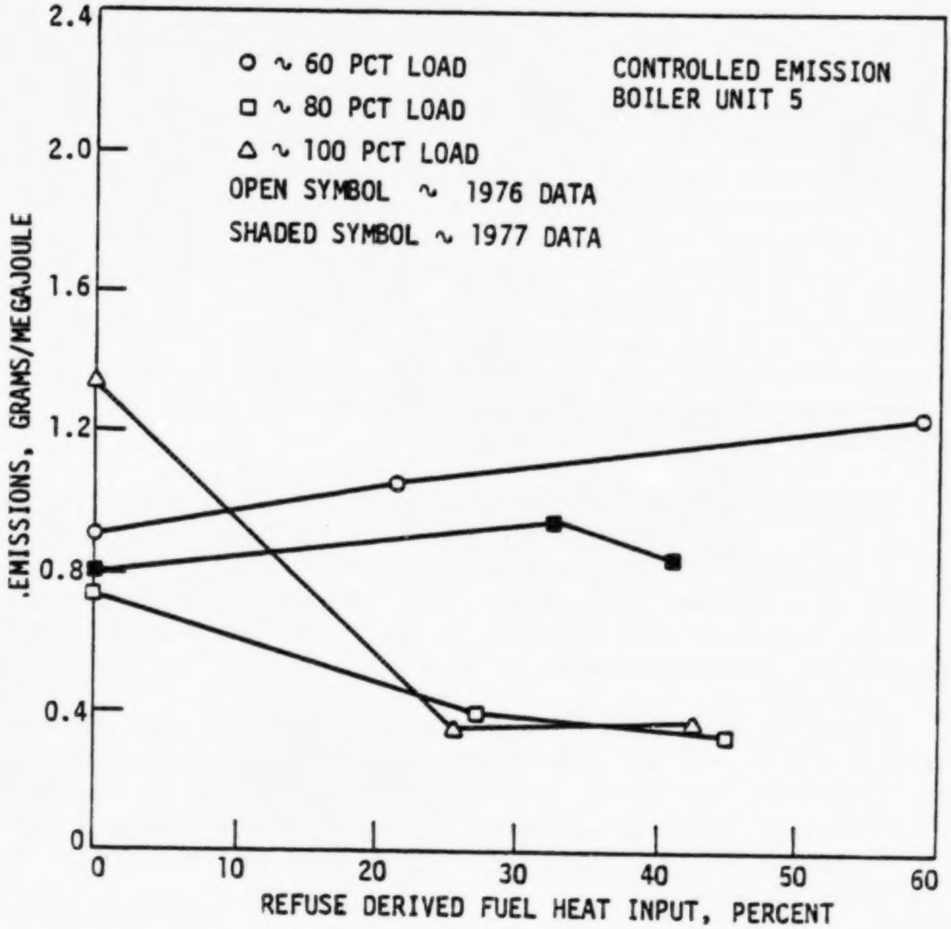

Figure 41. Controlled particulate emissions from stoker-fired boiler unit 5.

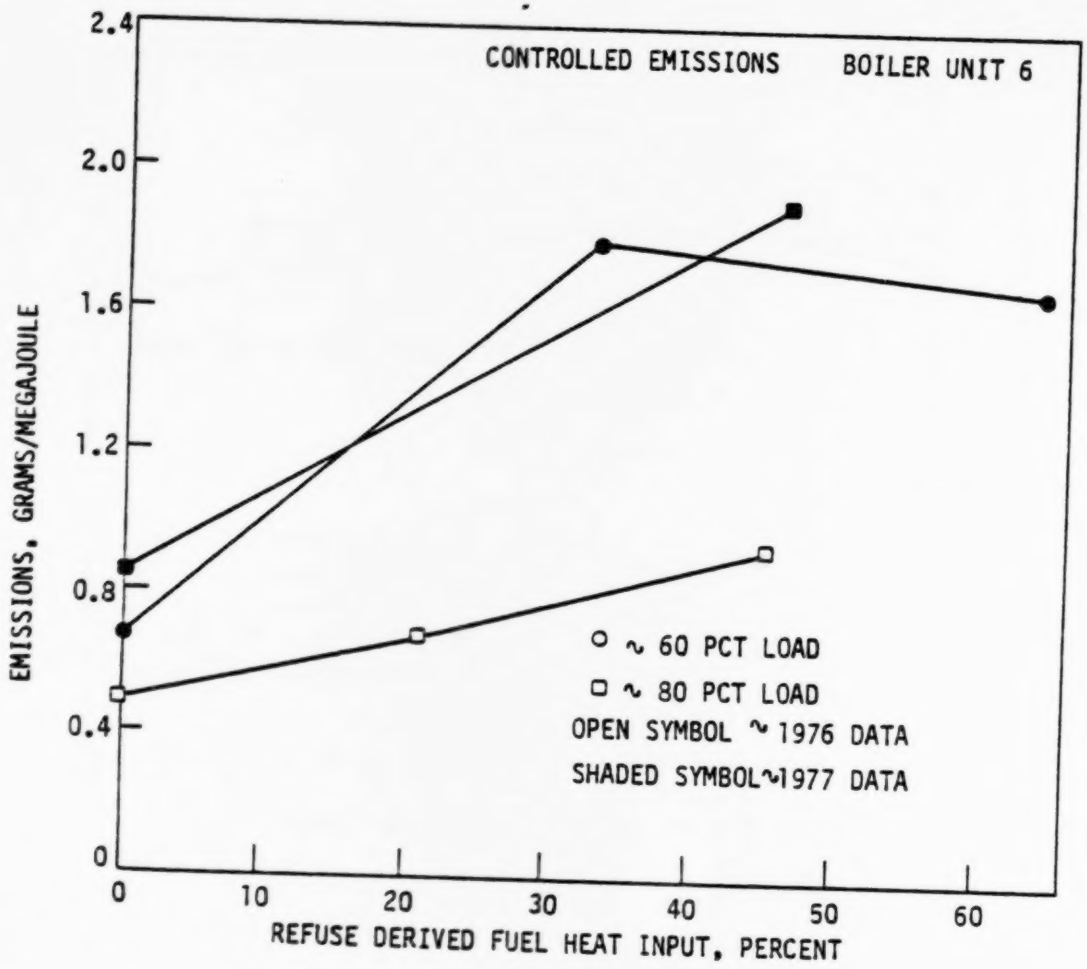

Figure 42. Controlled particulate emissions from stoker-fired boiler unit 6.

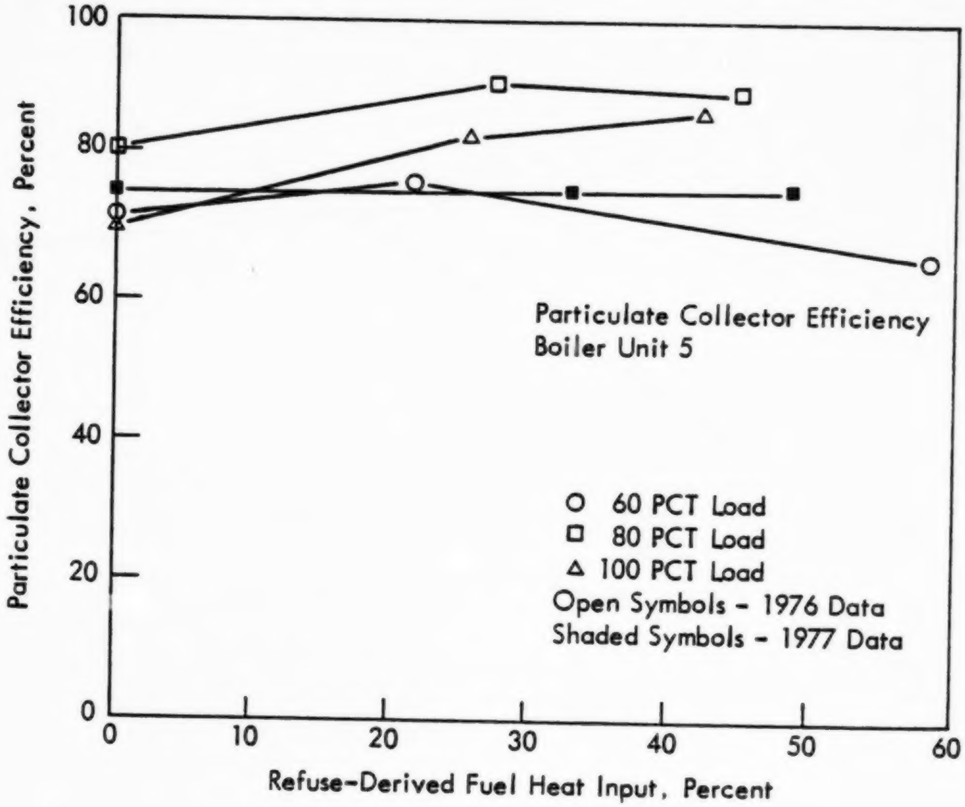

Figure 43. Mechanical collector efficiency for boiler unit 5.

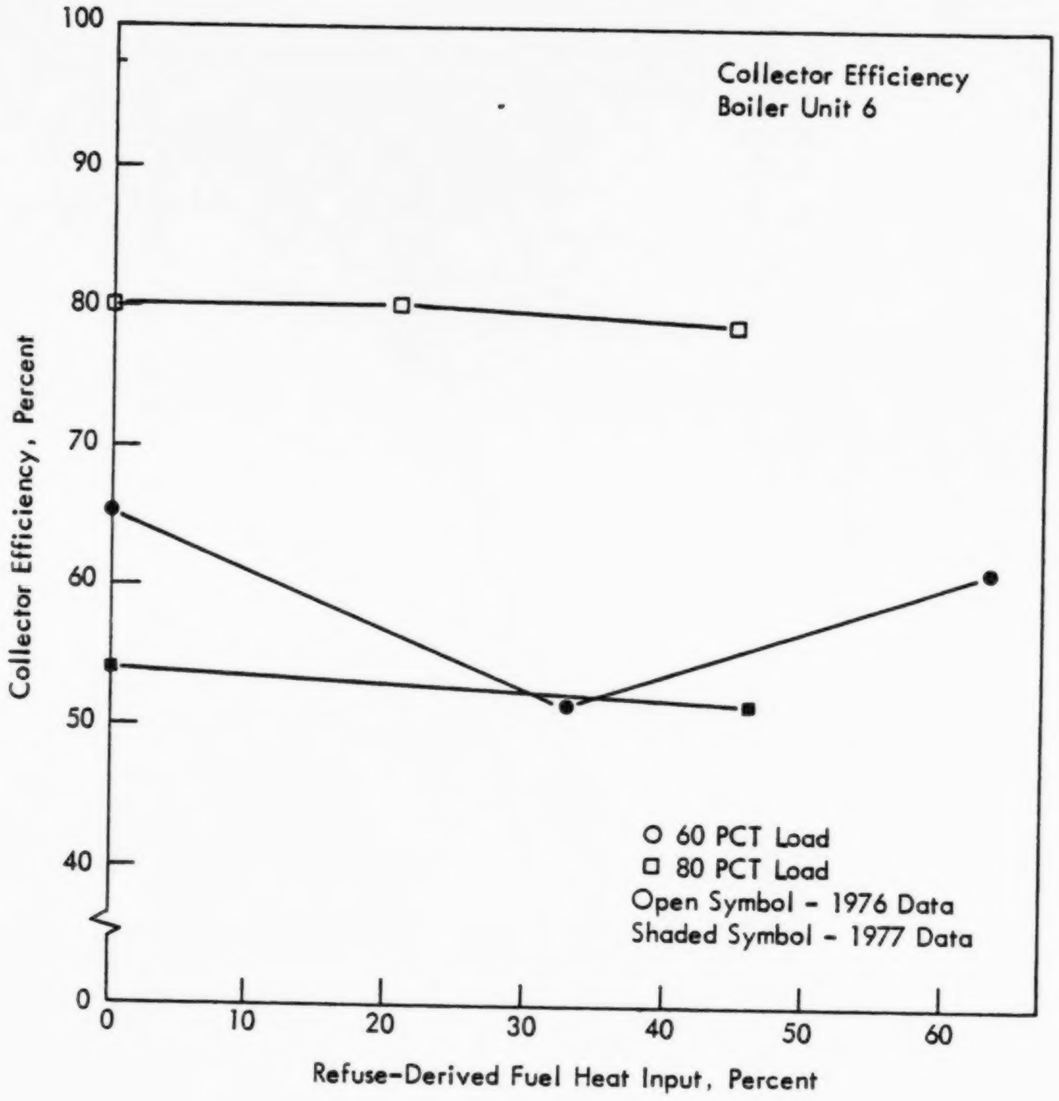

Figure 44. Mechanical collector efficiency for boiler unit 6.

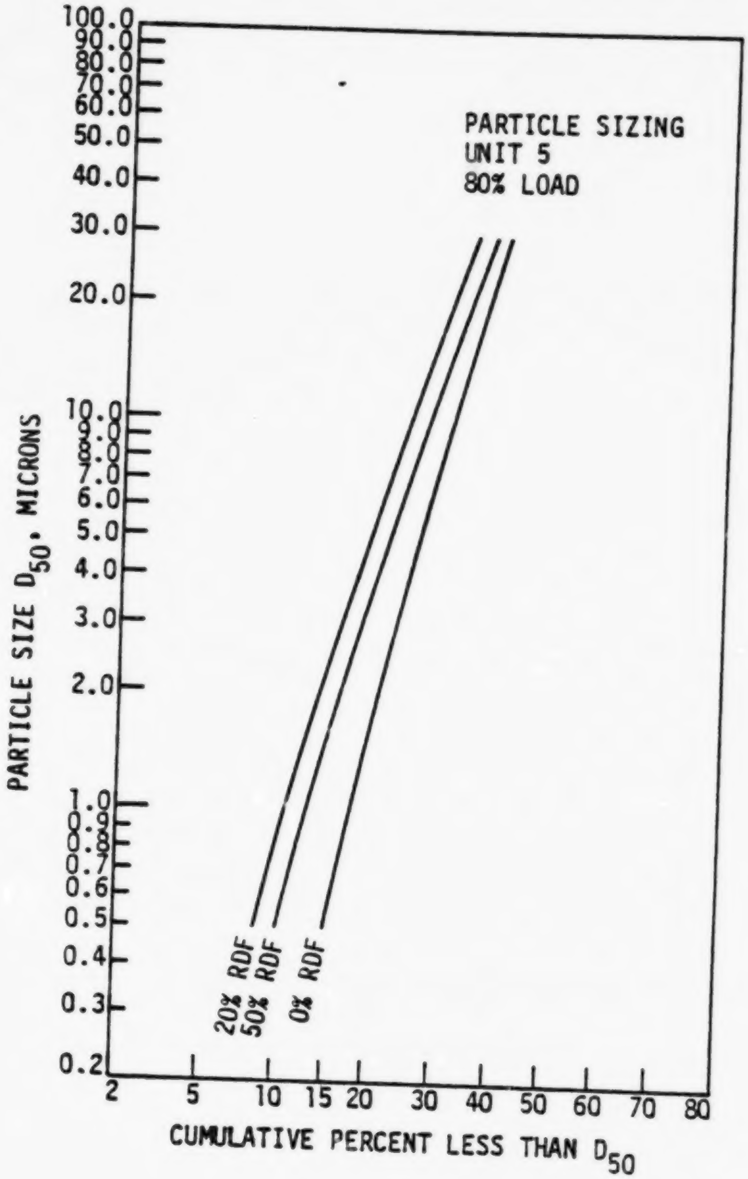

Figure 45. Relative changes in size of particulate emissions with increases in RDF for boiler unit 5.

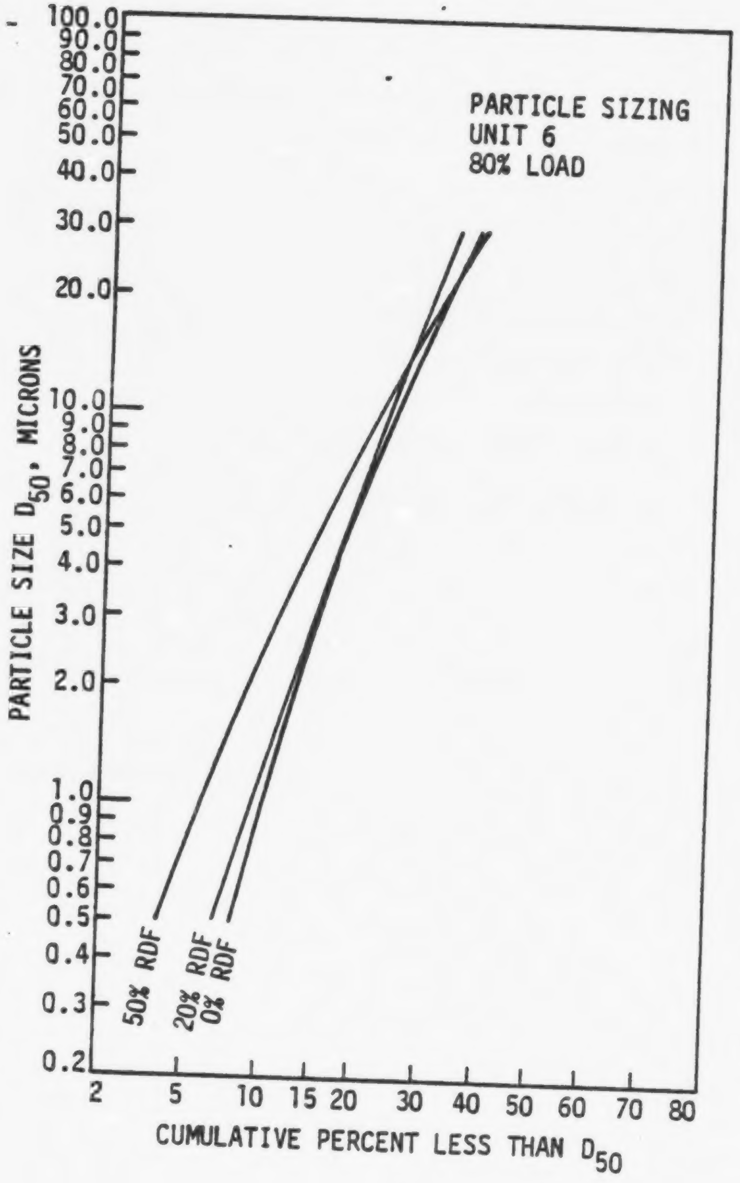

Figure 46. Relative changes in size of particulate emissions with increases in RDF for boiler unit 6.

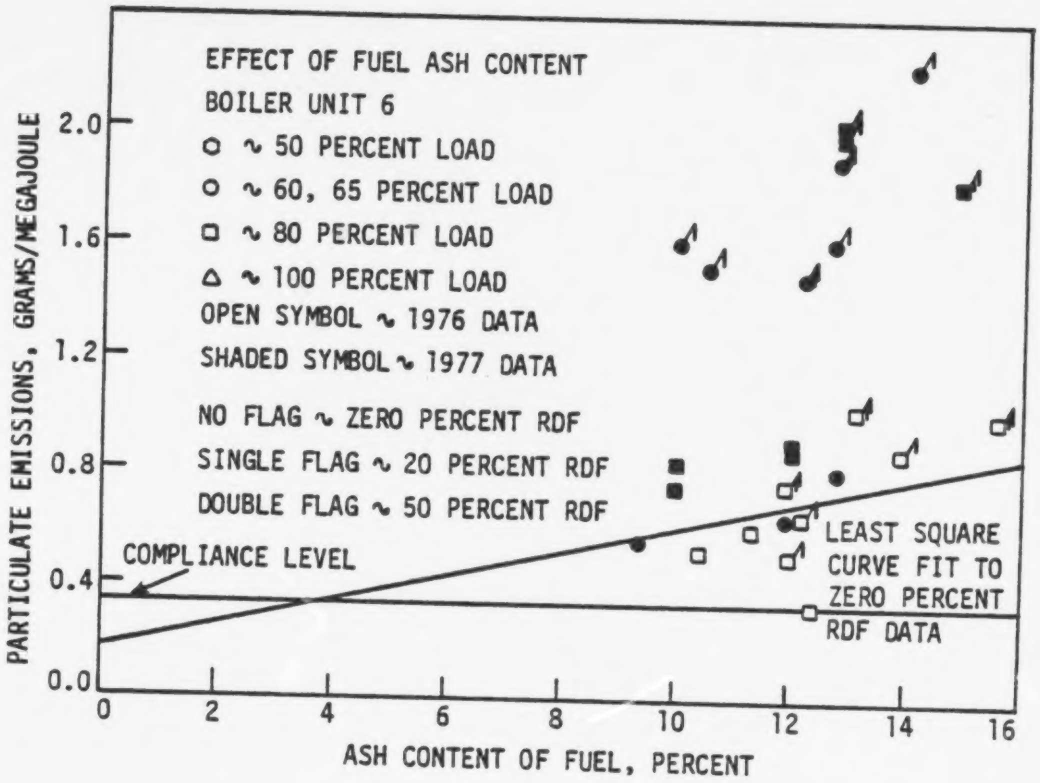

Figure 47. Stack particulate emission variation with ash content of fuel for boiler unit 6.

However, one advantage of a partially plugged slag screen is that it helps keep the particulate matter from being carried through the superheater into the economizer and particulate collector parts of the steam generator unit. With a clean slag screen, the particulate carry-over provides additional grain loading to the particulate collector. For unit 5, this effect is shown in Figure 48 as well as how stack particulate emissions increase linearly with ash content of the fuel. From Figure 48 it appears that ash content of the fuel significantly affects the particulate emissions from this combination of steam generator and particulate collector.

Oxides of Sulfur--

The oxides of sulfur (SO_x) emitted from the boilers decrease significantly with increases in RDF as shown in Figures 49 and 50. The effect was most pronounced when the low sulfur content RDF was mixed with high sulfur content Iowa coal. This decrease ranged from one-third to two-thirds at boiler loads of 80% from 0% RDF to 50% RDF mixtures with the Iowa-Wyoming coal and the Iowa coal, respectively. Thus, an advantage of using RDF with coal is that high sulfur coal can be used and still meet EPA regulations.

Oxides of Nitrogen--

The oxides of nitrogen (NO_x) generally decrease with increases in percentage RDF at all boiler loads as shown in Figures 51 and 52. The decrease was generally in the range of 10% to 40% and somewhat independent of boiler load. The NO_x emissions were generally less and the decreases much less for the 1977 data than for the 1976 data. This may represent better operation of the boilers and better control of the combustion zone temperatures for the experimental runs of 1977.

Chlorides--

The chloride emissions for both stoker-fired boilers increased linearly and significantly with increases in RDF as shown in Figures 53 and 54. Each boiler showed as much as a tenfold increase in chloride emissions as the RDF increased from 0% to 50% for all boiler loads.

No conclusive trends concerning aldehyde and ketone emissions (reported as formaldehyde) could be observed as illustrated in Figures 55 and 56. These emissions depend on the constituents of the RDF such as wood chips, leaves, and other cellulose fiber. No control of the quantity of these items in the RDF was attempted. Consequently, the emissions due to the burning of cellulose fiber were as variable as the constituents of the RDF.

Hydrocarbons--

The unburned hydrocarbons in the C_1 to C_5 range emitted from the stack were quite variable, as were the constituents of the RDF routed to the stoker-fired boilers. No conclusive trend could be ascertained from the data as illustrated in Figures 57 and 58.

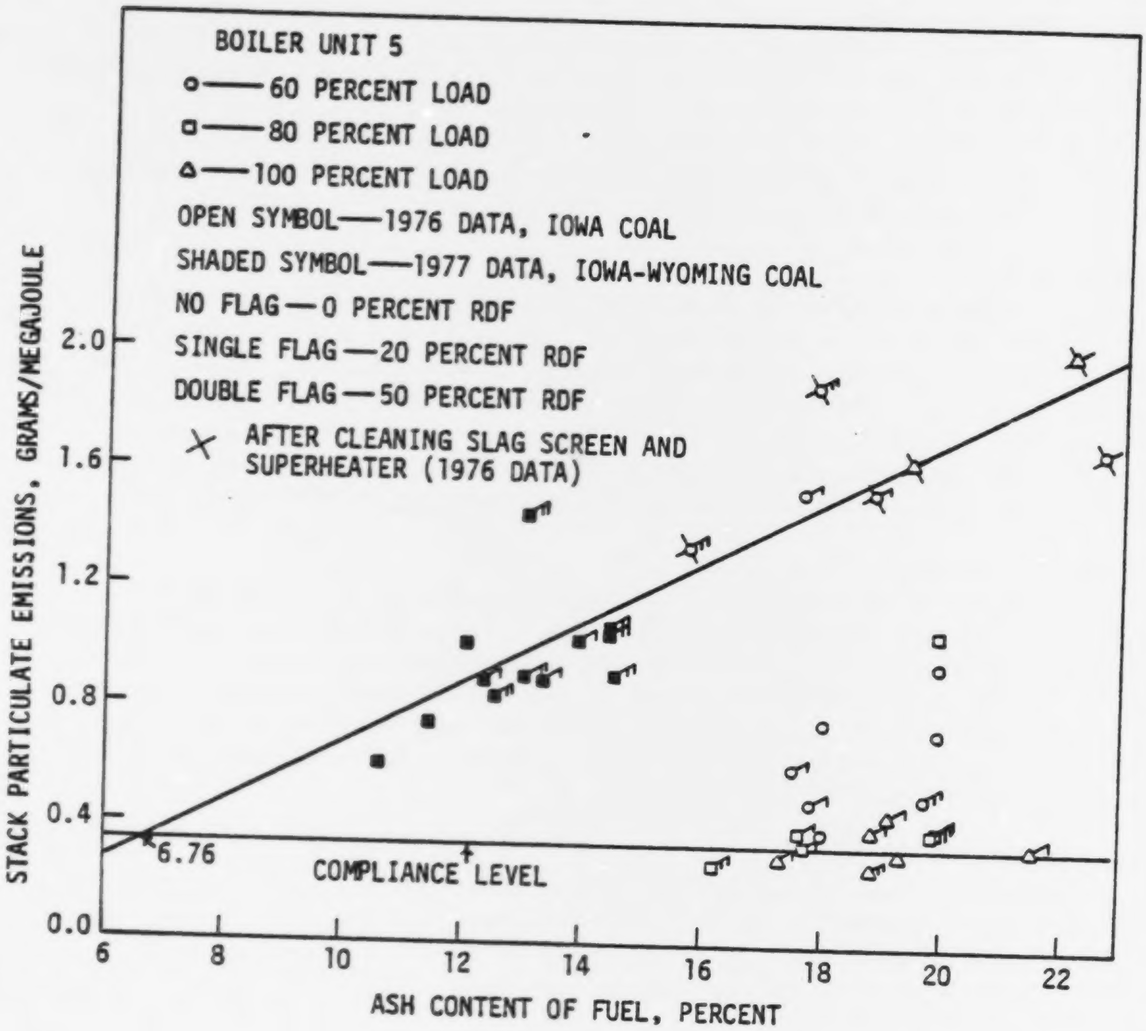

Figure 48. Stack particulate emission variation with ash content of fuel for boiler unit 5.

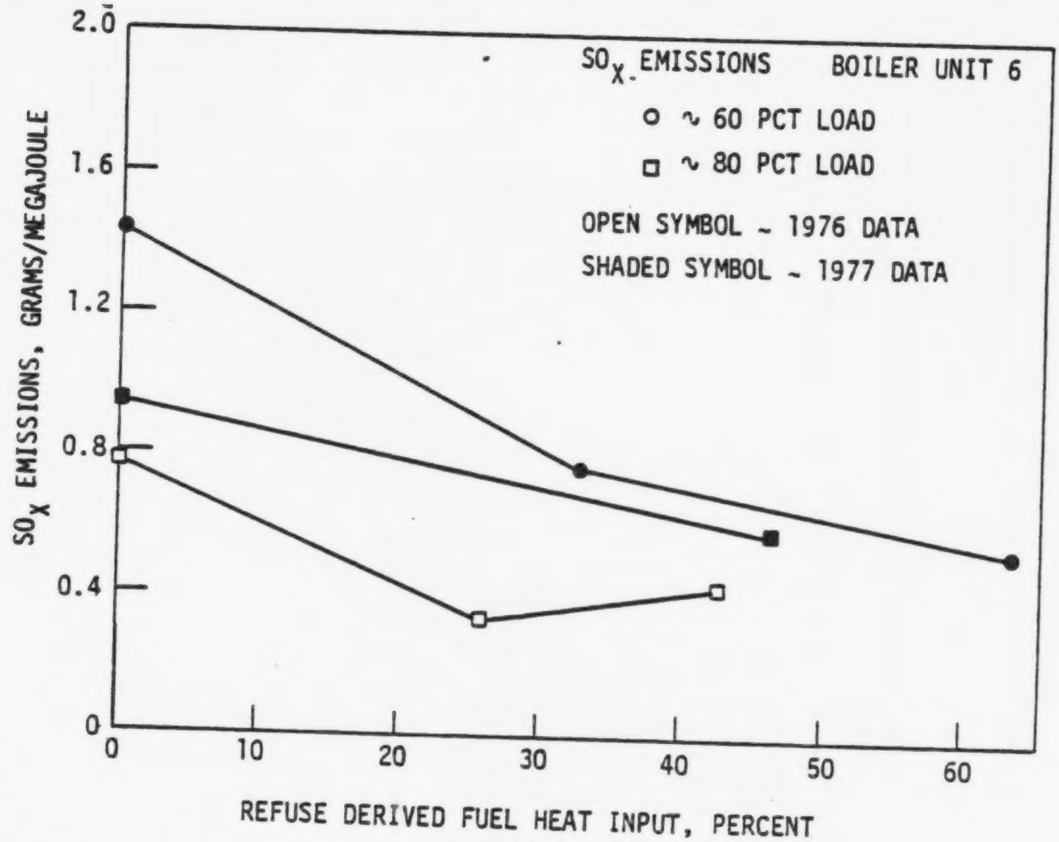

Figure 49. Sulfur emissions from stoker-fired boiler unit 6.

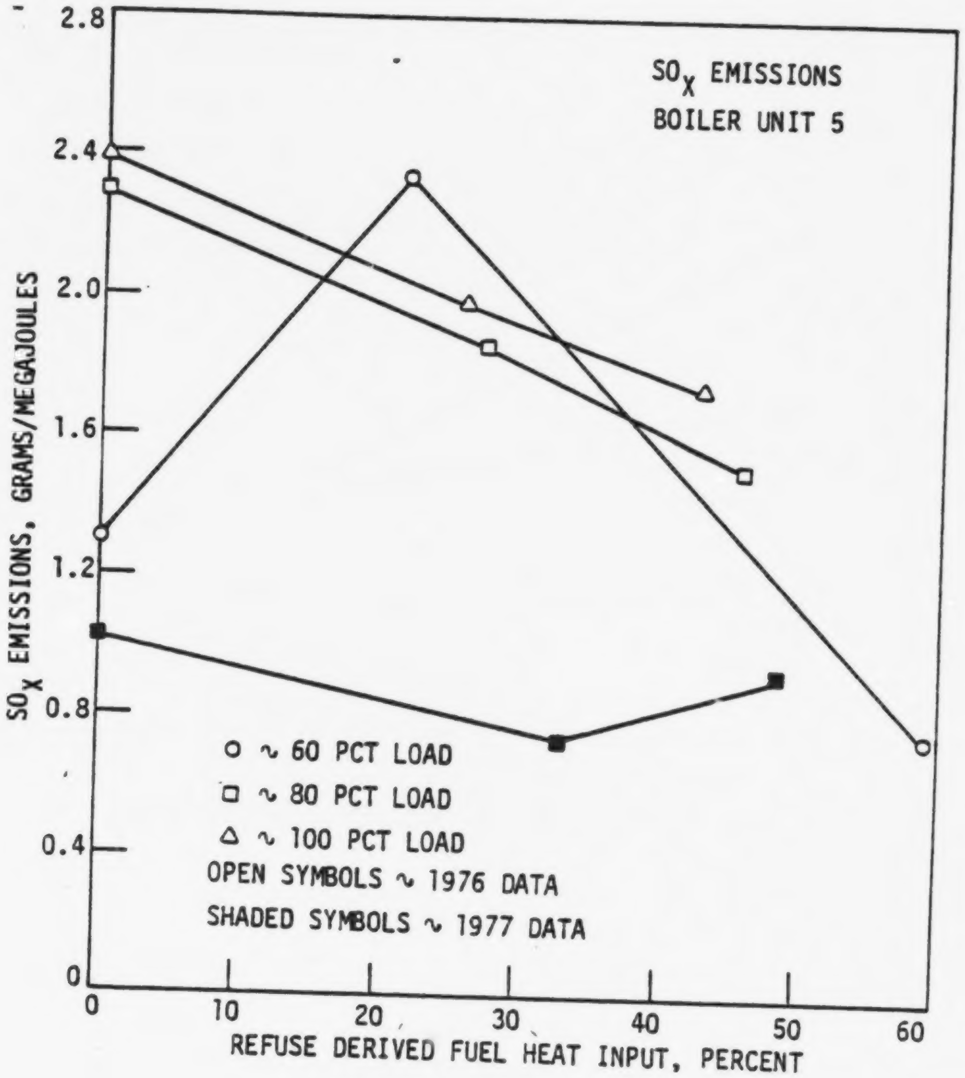

Figure 50. Sulfur emissions from stoker-fired boiler unit 5.

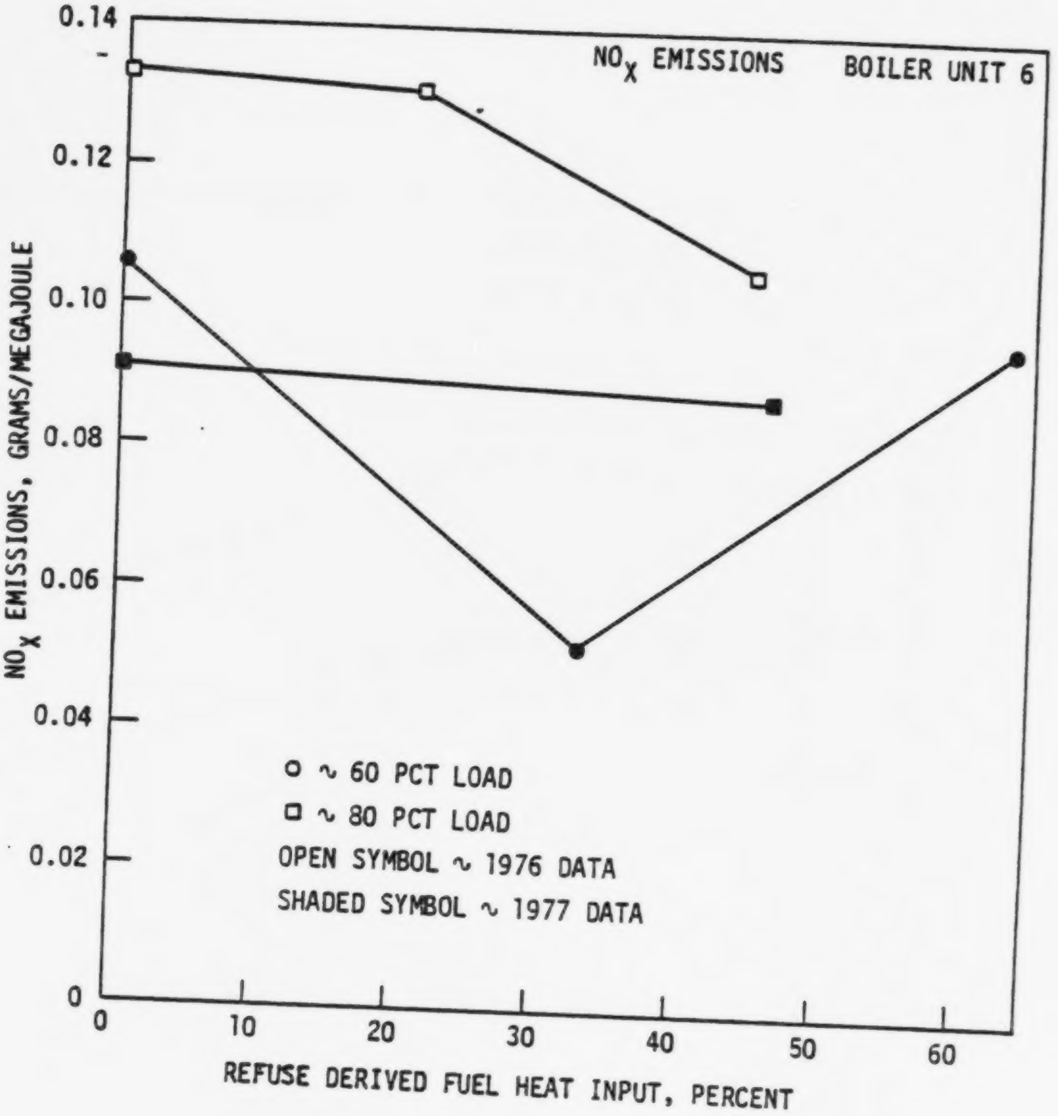

Figure 51. Oxide of nitrogen emissions from stoker-fired boiler unit 6.

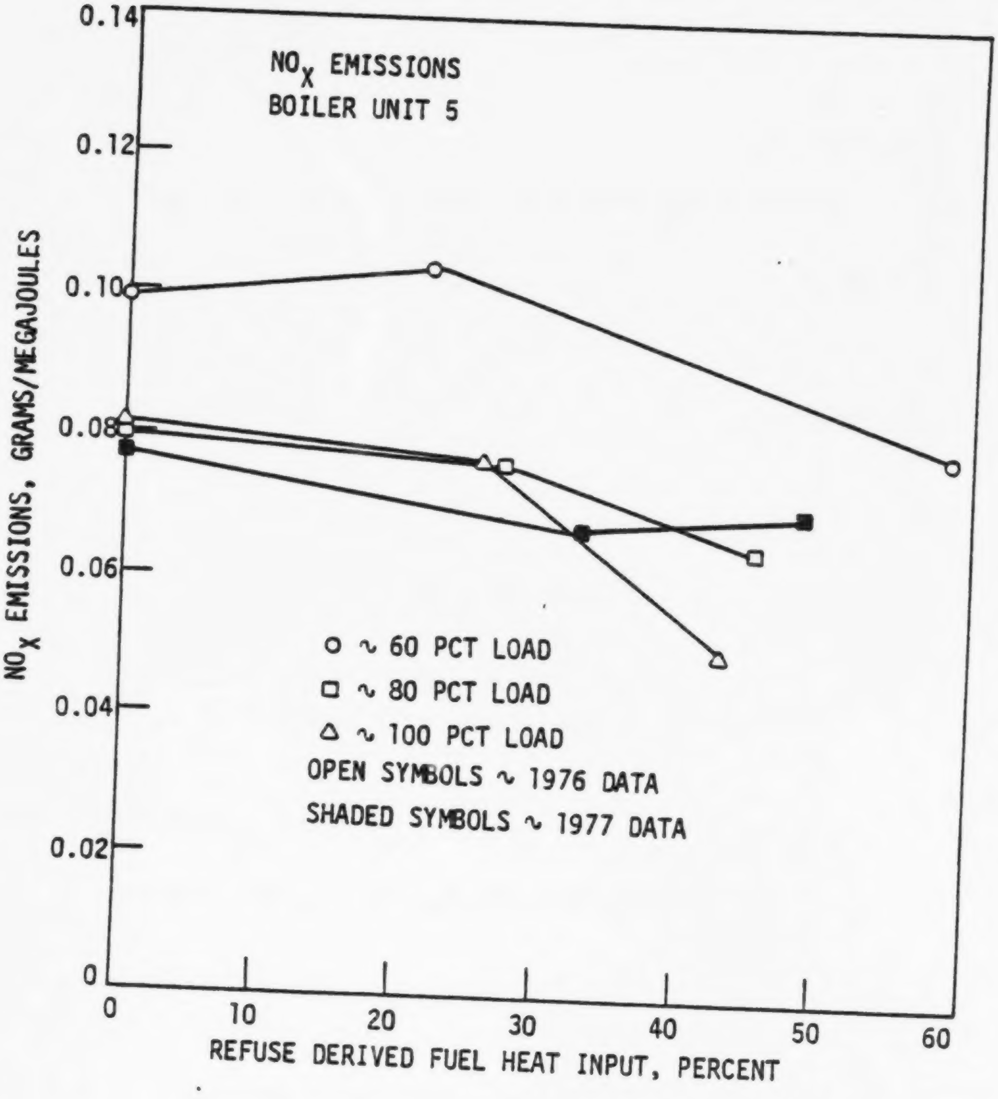

Figure 52. Oxide of nitrogen emissions from stoker-fired boiler unit 5.

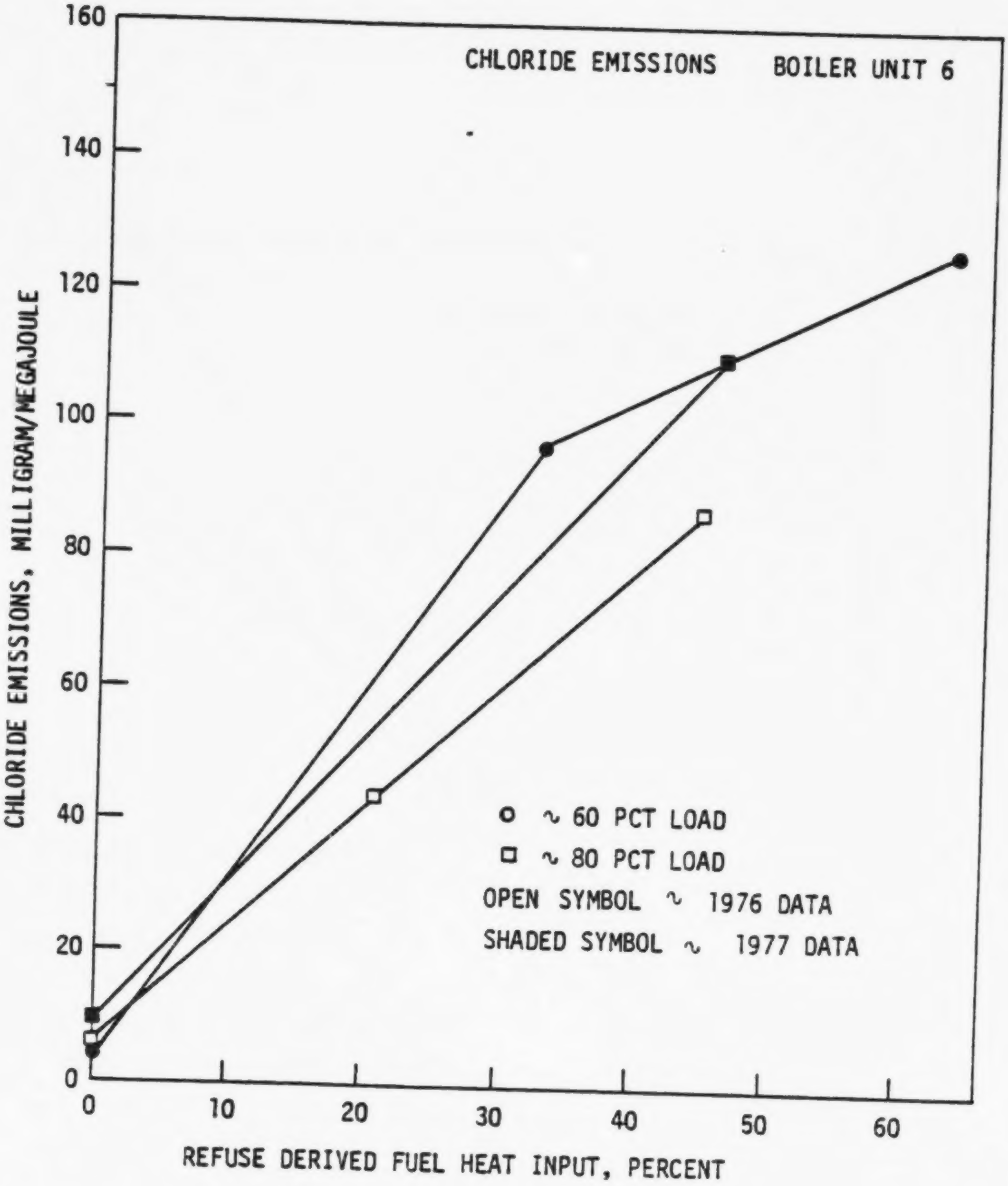

Figure 53. Chloride emissions from stoker-fired boiler unit 6.

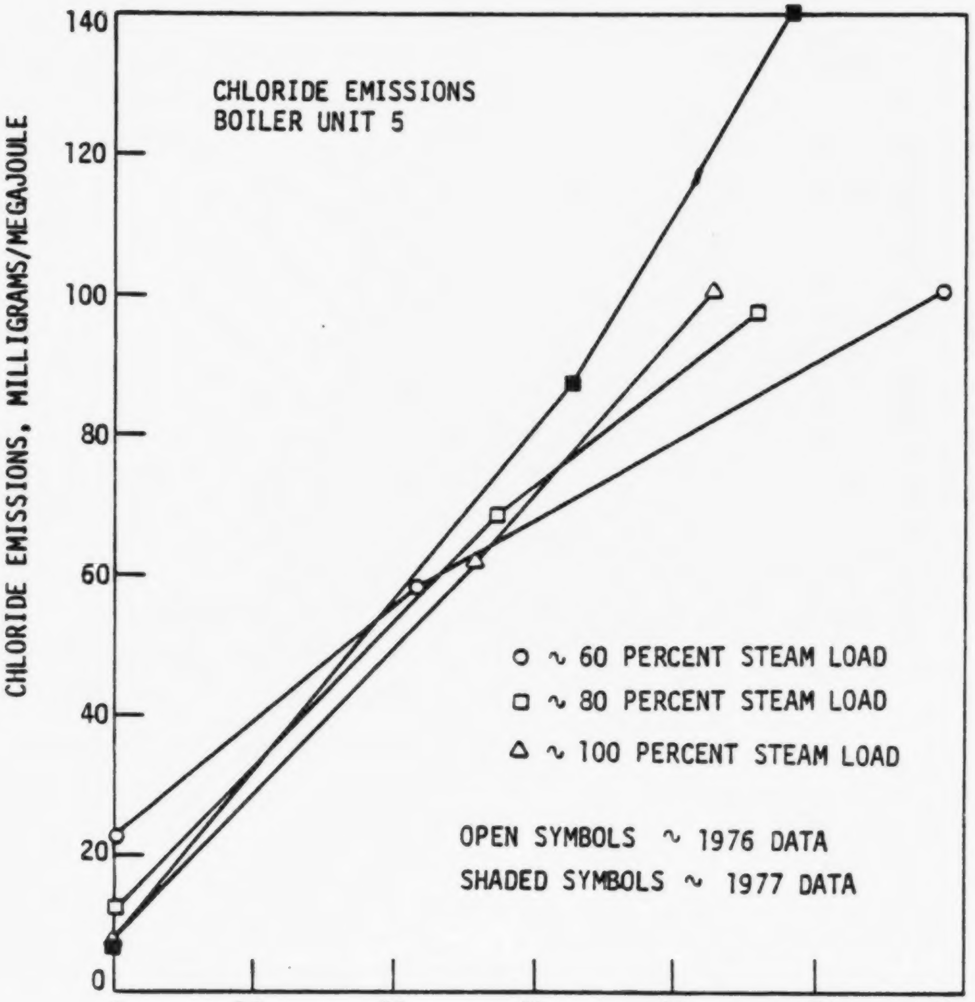

Figure 54. Chloride emissions from stoker-fired boiler unit 5.

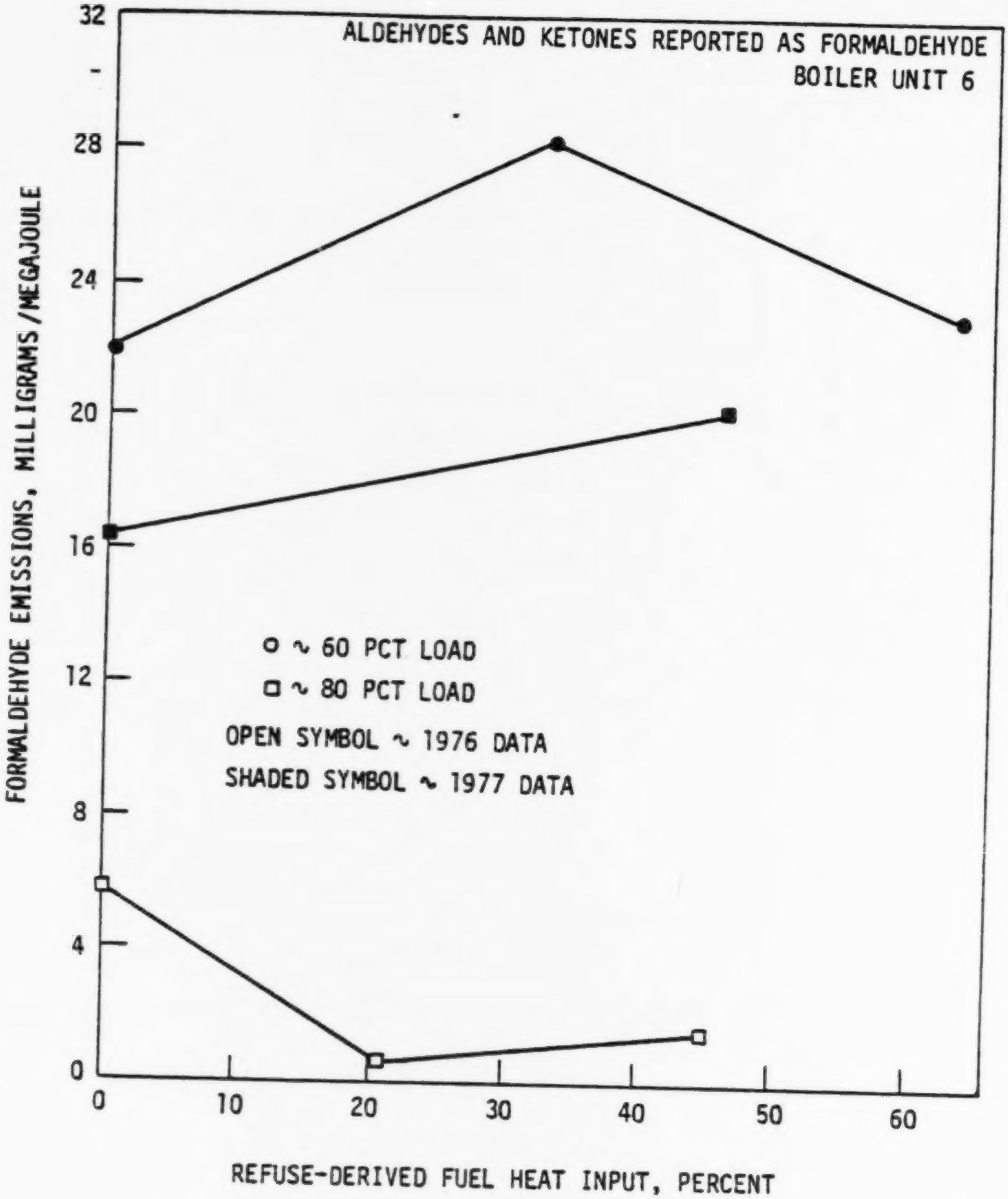

Figure 55. Formaldehyde emissions from stoker-fired boiler unit 6.

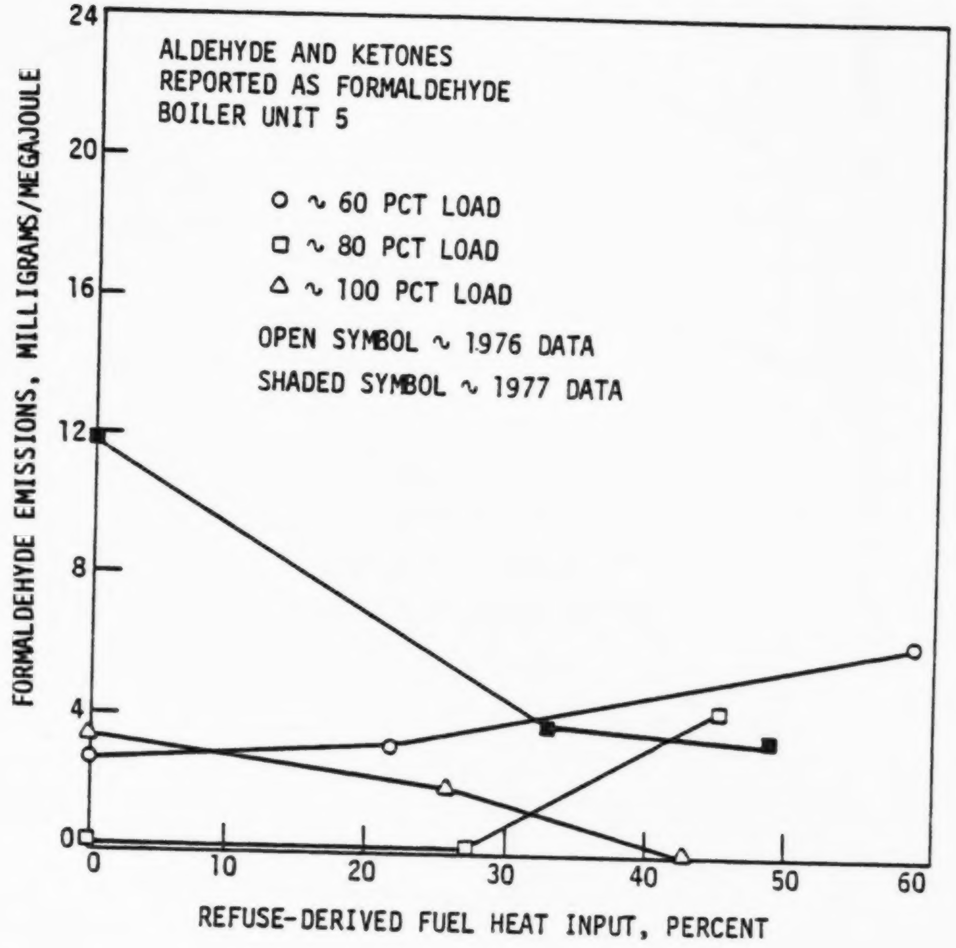

Figure 56. Formaldehyde emissions from stoker-fired boiler unit 5.

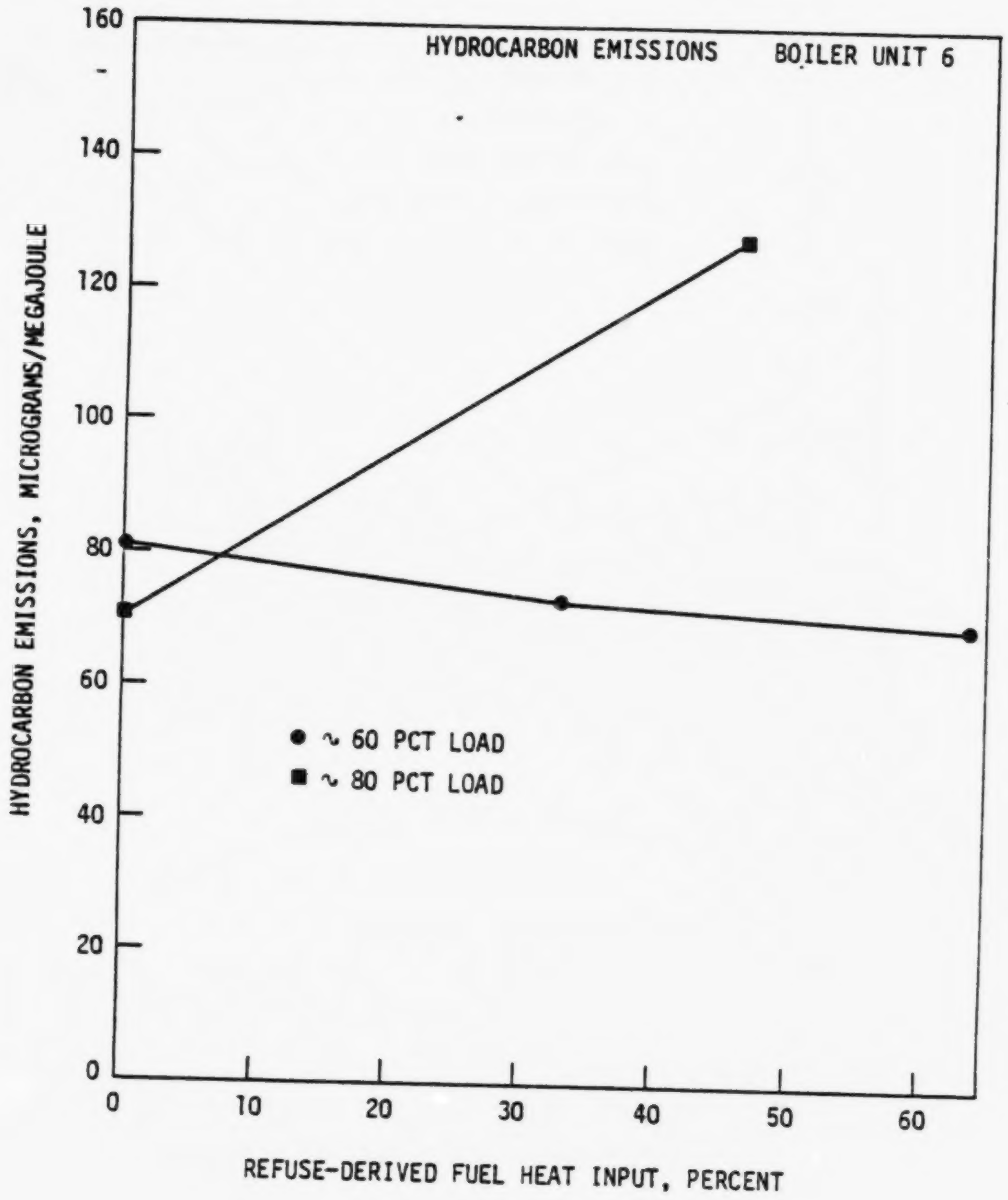

Figure 57. Hydrocarbon emissions from stoker-fired boiler unit 6.

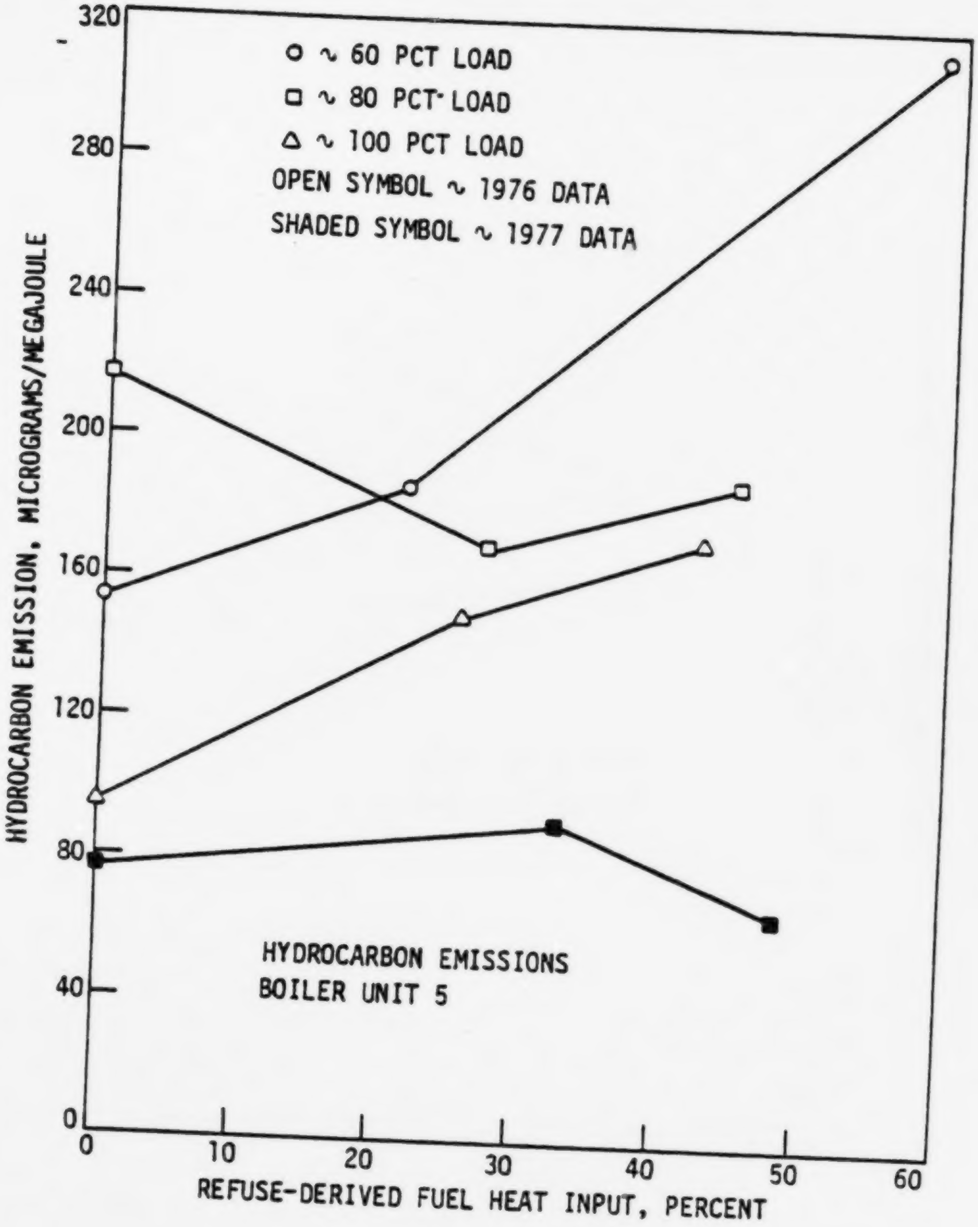

Figure 58. Hydrocarbon emissions from stoker-fired boiler unit 5.

Total gas chromatographable organics collected on the macro-reticular resin column showed no discernible trend with percentage RDF burned. As with the particulate emissions reported earlier, there was considerable variability between samples. Total organics were somewhat higher for unit 5 than for unit 6. This is thought to be due to the more complete oxidizing conditions that could be obtained in unit 6.

Seven polynuclear aromatic hydrocarbons (PAHs) were monitored on the hopper ash as a function of percentage RDF burned. Four PAHs (3,4-benzopyrene, 3-methyl cholanthrene, dibenz(A,H)anthracene, and 3,4,9,10-dibenzopyrene pyrene) were not detected. Fluorene, fluoranthene, and pyrene were present, but concentrations were low and did not vary with percentage RDF burned. All seven of the PAHs or other members of the same compound classes, were identified in the stack vapors.

An evaluation of polychlorinated biphenyls (PCBs) was made during the extraction, clean-up, and separation procedure reported by Reference 19. PCBs were found in the RDF at levels near 1 ppm though none were detected in the coal. PCBs were detected at a level of a few parts per billion on particulates collected from the stack. No trends with percentage RDF have been observed. The PCBs were not detected on hopper ash, suggesting that they may be deposited on the particulates as the stack gases cool.

Trace Elements--

Particulate emissions, as collected on the filter of the EPA Method 5 sampling train, were also analyzed for 19 trace elements. Only iron and germanium definitely decreased with increases in RDF. Only zinc, copper, lead, and gallium showed highly significant increases with RDF over coal-only. Zinc comes into refuse-derived fuel from white paper where it is used as a filler material. Lead and copper come into RDF from inks used in newsprint and colored pictures. The gallium is thought to be an impurity that comes into the RDF along with another element such as aluminum.

The enrichment factor (20) of zinc, copper, lead, and gallium increased by more than a factor of 10 as the RDF increased from 0% (coal-only) to 50% as illustrated in Figures 59 and 60 for boiler loads of 80%. It can also be observed in Figures 59 and 60 that all of the other trace elements plotted increased by a factor of 5 or less as RDF increased to 50%.

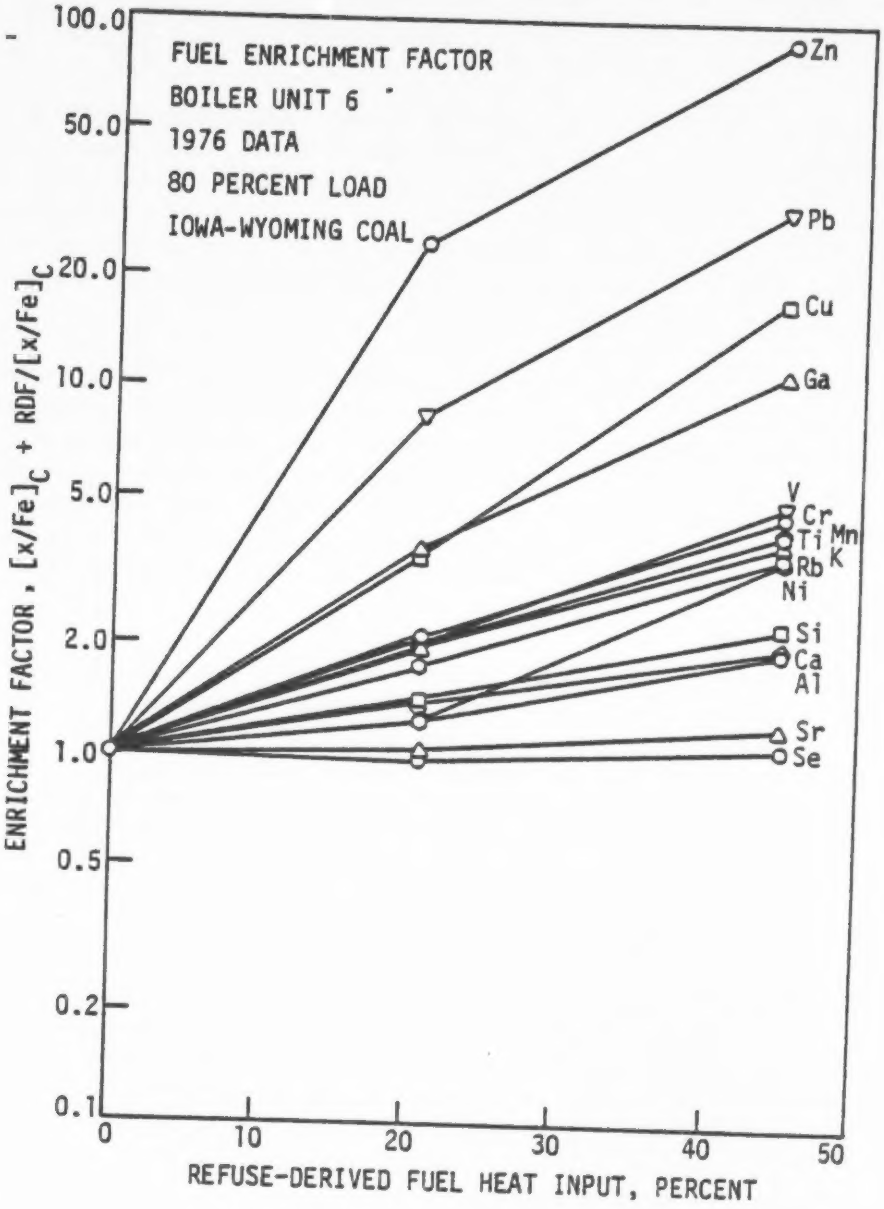

Figure 59. Fuel enrichment factor variation with RDF for boiler unit 6.

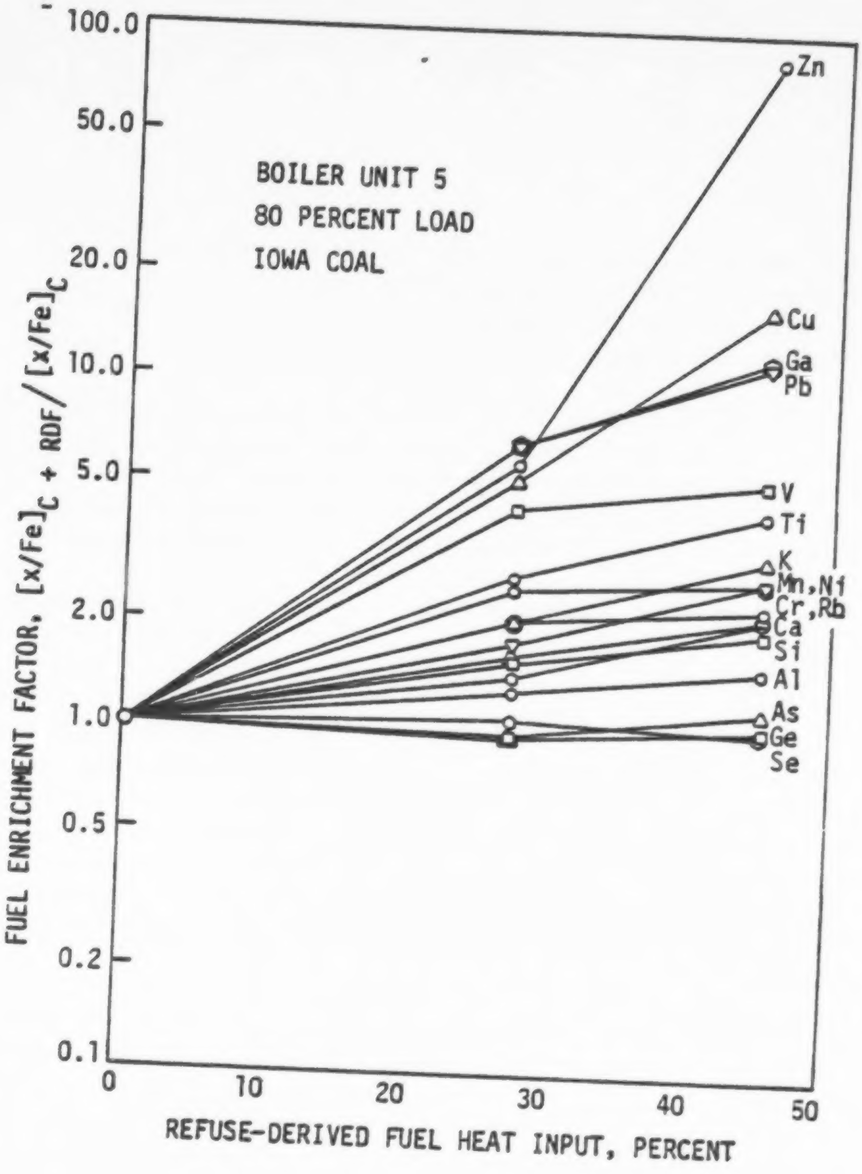

Figure *60*. Fuel enrichment factor variation with RDF for boiler unit 5.

The fuel enrichment factor (FEF) in Figures 91 and 92 is defined by the relation:

$$\mathrm{FEF} = \frac{\dfrac{[x]_{C + RDF}}{[FE]_{C + RDF}}}{\dfrac{[x]_{C}}{[Fe]_{C}}} = \frac{[x/Fe]_{C + RDF}}{[x/Fe]_{C}} \qquad (1)$$

where

x = grams of trace elements x/MJ of heat energy input
Fe = grams of iron/MJ of heat energy input
C = subscript meaning coal only at the input
C + RDF = subscript meaning mixture of coal and RDF at the input

This fuel enrichment factor was derived in part from Gladney (20). The fuel enrichment factor is a method of comparing the relative quantity of one element in an input or output stream to the relative quantity of that same element in a reference stream. The relative quantity of an element is determined by a ratio with some reference element in the same stream.

Iron was chosen as a reference because its value was measured more precisely than any other element in the samples of these tests. This is mainly because the quantity of iron in the samples is quite high and significantly above the detection limits or resolving ability of the x-ray fluorescence apparatus used for trace element analysis. The ratio of the amount of element to the amount of iron was formed to help eliminate or cancel any calibration factors in the analytical apparatus that would be of a multiplicative nature. This was felt to be of importance because many of the trace elements scanned were only slightly above the detection limits of the apparatus. Thus, elimination of as many uncertainties as possible in the data led to the use of the enrichment factor for presentation of the trace element results.

For each trace element entering the boiler in the fuel, an attempt was made to determine where the element leaves the steam generator. Portions of each element can be expelled in the grate ash, fly ash hopper, or stack effluent. To determine this, enrichment factors and emission ratios were ascertained from samples of grate ash, fly (hopper) ash, and stack particulate effluent obtained during test runs. Typical results are shown at 80% load for lead in Figures 61, 62, 63, and 64. Results for the other trace elements are not included because of space limitations.

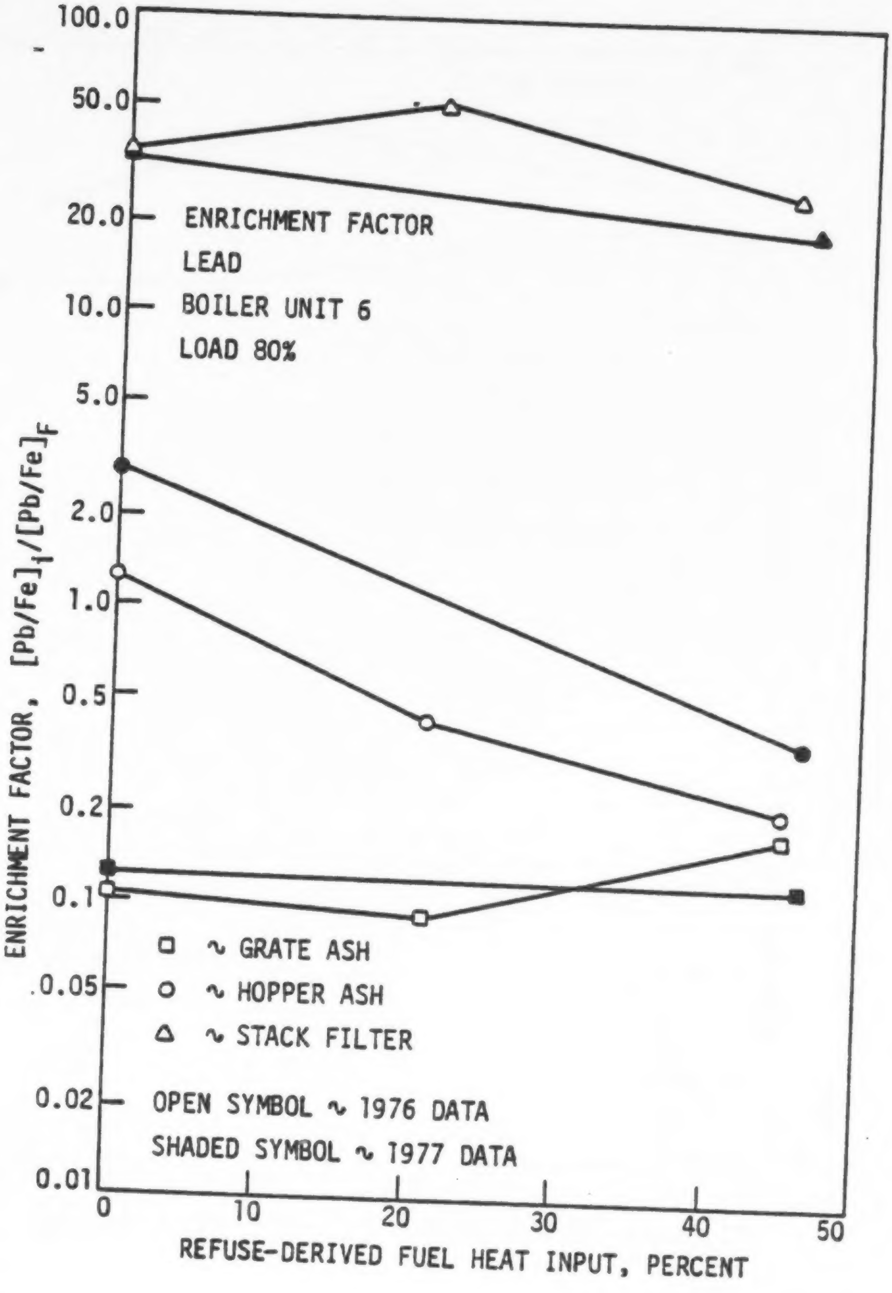

Figure 61. Lead enrichment factor variation with RDF for boiler unit 6.

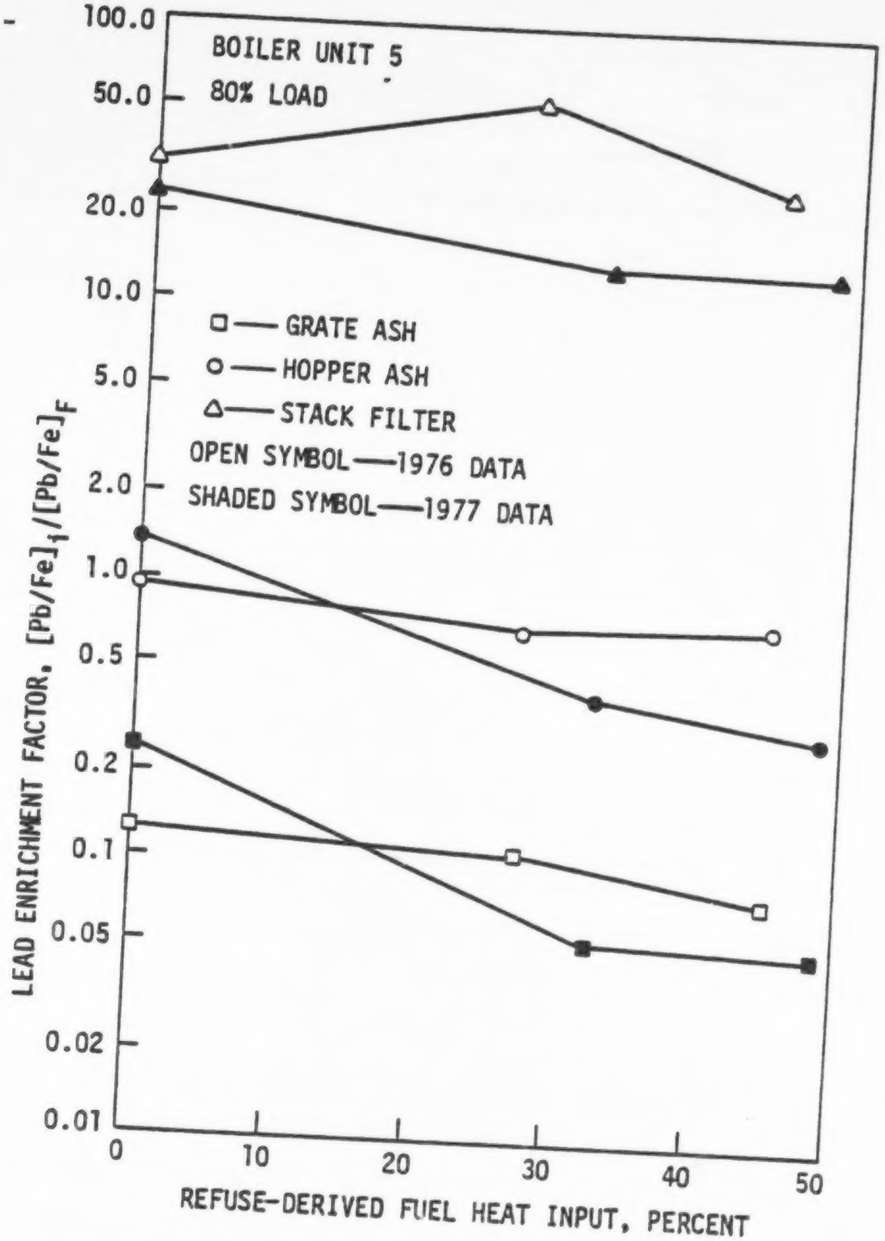

Figure 62. Lead enrichment factor variation with RDF for boiler unit 5.

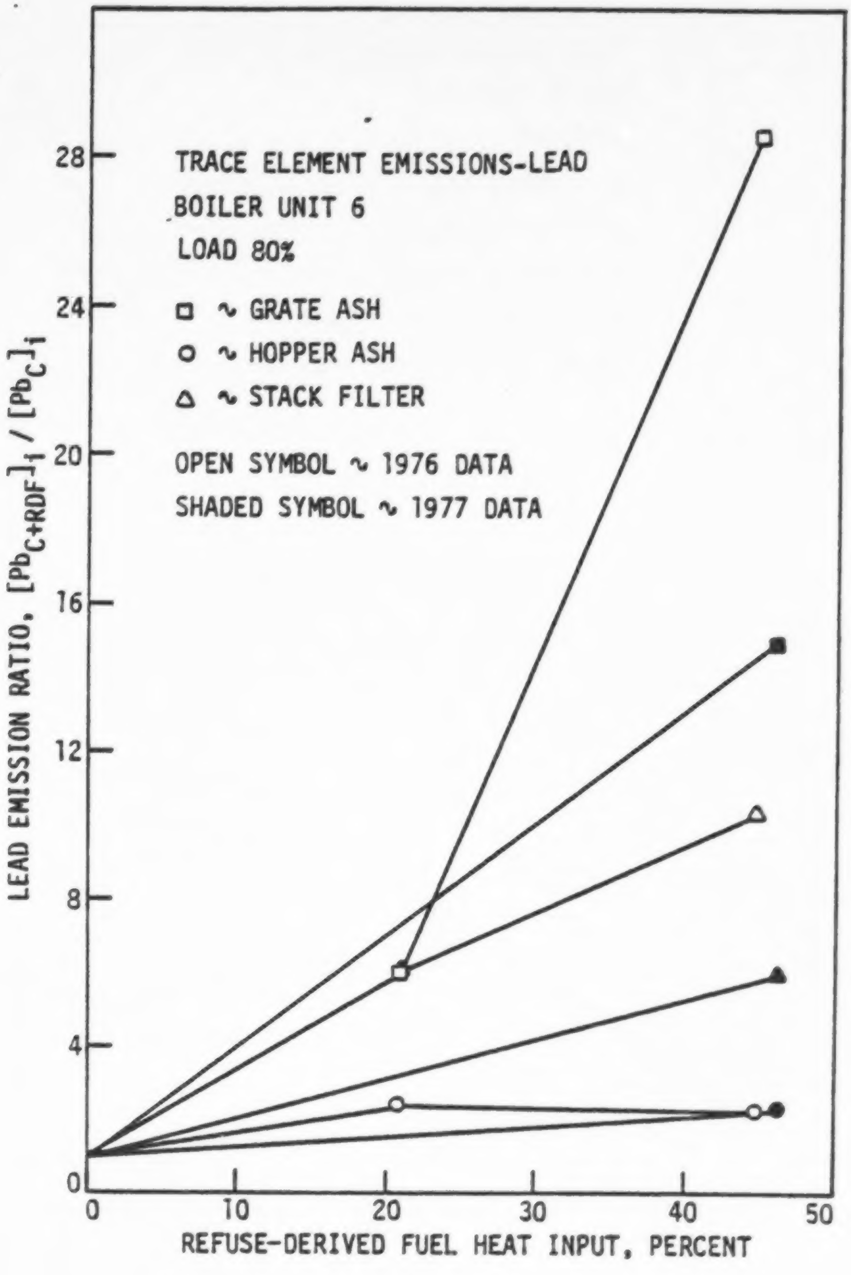

Figure 63. Lead emission ratio variation with RDF for boiler unit 6.

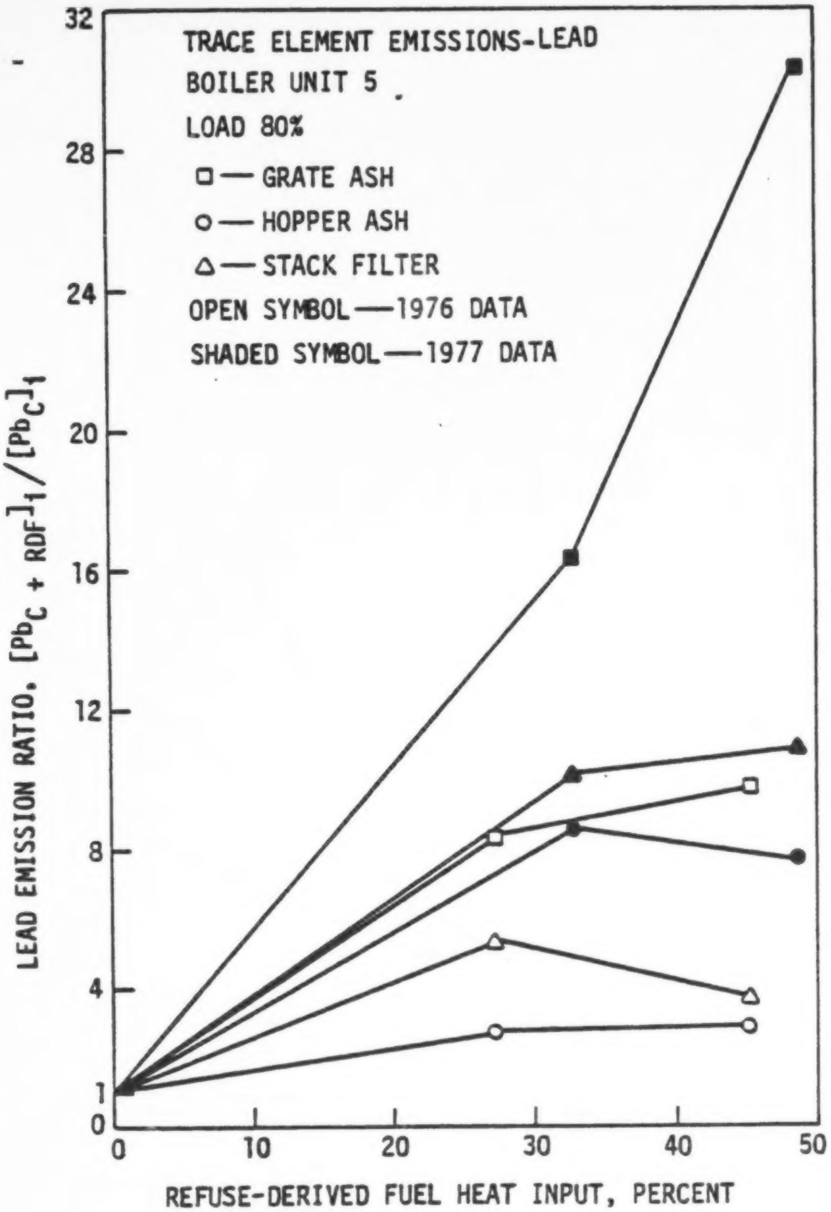

Figure 64. Lead emission ratio variation with RDF for boiler unit 5.

The enrichment factor (EF) used in Figures 61 and 62 is defined by the relation:

$$\overline{\mathrm{EF}}_i = \frac{\dfrac{[x]_i}{[\mathrm{Fe}]_i}}{\dfrac{[x]_F}{[\mathrm{Fe}]_F}} = \frac{[x/\mathrm{Fe}]_i}{[x/\mathrm{FE}]_F} \quad . \qquad (2)$$

where

i = subscript meaning ith sampling location (e.g., grate, hopper, or stack)

F = subscript meaning fuel at the input (may be either coal-only or a mixture of coal and RDF)

The emission ratio (ER) used in Figures 63 and 64 is defined by the relation:

$$\mathrm{ER}_i = \frac{[x]_i}{[x]_{C_i}} = [x/x_C]_i \qquad (3)$$

Figure 62 indicates that as an increase in RDF occurs the relative proportions of lead being expelled decrease in the grate ash, decrease in the hopper ash, and stay about the same proportion in the stack effluent. This is especially the case for the most recent (1977) data.

Figure 64 indicates that the amount of lead being expelled increases by a much smaller factor in the hopper (fly) ash and the stack than in the grate ash. Some of the lighter trace elements such as zinc show a much higher dropout in the stack effluent than in the grate or hopper ash. These trace elements apparently vaporize during the combustion process and leave the combustion chamber of the boiler. The vapor then condenses on the fly ash particles and surfaces of the superheater, economizer, collector, and stack as the temperature drops outside the combustion zone.

It is thought that the levels of the trace elements are sufficiently low in most cases to be harmless. However, appropriate threshold levels for harm are either unknown or have not been established for many of the trace elements of this study. Further data on the trace elements are currently being studied and prepared for publication.

CONCLUSIONS

RDF in combination with coal was successfully fired in the stoker boilers with no insurmountable problems. The operation of the boiler improved in terms of stability and consistency of measured variables from 1976 to 1977. This is believed to be a "learning effect" on the part of the boiler operators in properly firing the RDF and coal mixtures.

The combustible properties of the fly ash and the bottom (grate) ash became similar as the RDF approached 50%. The ash softening point of the ash lowered and the fouling index became more detrimental as the RDF was increased in the fuel input.

Uncontrolled particulate emissions tended to increase with corresponding increases in the RDF fraction of fuel input. This appears to be a result of both lighter particulates and increases in air flow through the boiler when burning RDF. Controlled emissions also appeared to increase with increases in RDF on unit 6, but the trend was uncertain on unit 5.

Both the oxides of nitrogen (NO_x) and oxides of sulfur (SO_x) decreased while chlorides increased significantly with increases in RDF. No discernible trends within the data scatter were noted concerning formaldehyde or hydrocarbon emissions. Increased emissions of the trace elements copper, lead, and zinc corresponded to increases in RDF. Further studies of the trace element emissions are being performed.

Further studies are still in progress at the Ames facility. Thus, more specific conclusions cannot be made at this time. The final data from Ames, both economic and technical, will provide valuable design information for future plants and will aid operators of existing waste-to-energy plants.

SECTION 7

CORROSION INVESTIGATION

BACKGROUND

The work in this section is a continuation of that reported as Section 8 of Part II of the previous report, "Evaluation of the Ames Solid Waste Recovery System" (7).

The earlier report described some of the results of a 1,000-hr test of waterwall and superheater tubes in boiler Unit 5. This report further discusses some of the prior results and also describes tests run under similar conditions for approximately 1 year. These findings are compared with test results from water wall and superheater tubes which had been continuously in place and in service since the original construction of the boiler.

DISCUSSION OF PRIOR RESULTS

Metallographic Procedures

In the earlier report, several photomicrographs (Figures 41, 42, and 43 of that report) were presented which appeared to show a black oxide layer adjacent to the surface of the superheater tube. Subsequent work has shown that this material is an oxide but that it is formed as an artifact of metallographic polishing. All metallographic specimens were mounted in a plastic material (diallyl phthalate) containing large amounts of flake copper. This material was used in order to make the mount electrically conductive for subsequent scanning electron microscope examination. Apparently the water slurry of polishing compound served as the electrolyte between the copper mount and steel specimen, thus forming an electrolytic cell which corroded the steel nearest the copper. This problem was solved by using methyl alcohol as the abrasive carrier and by minimizing the time interval between the end of final polishing and the onset of cleaning or etching.

In metallographic examinations performed following this change in procedure, no further "black oxide" was found. Black regions were occasionally noted which could be accounted for by cracks in the oxide layer or between it and the metal, but the concept of a distinct black phase formed during specimen exposure must be abandoned. There appear to be no other observations or conclusions of the prior report which are materially affected by this discovery.

Superheater Corosion Mechanism

Following the correction of the metallographic procedure, the same superheater specimen previously described was repolished and reexamined. This was a portion of an SA209, Grade T1 carbon molybdenum steel tube exposed for 1,018.5 hr during the burning of a fuel composed of approximately half coal and half RDF (on a Btu basis). The coal was an approximately equal blend of Iowa and Wyoming coal.

Figure 65 (negative 23835) is a photograph taken at 100X of the specimen in an unetched condition. The black specks in the light metal phase are inclusions. The scale-metal interface is undulating. There is a fairly sharp straight line of demarcation between the scale and the heterogeneous deposit. Beyond the deposit is the mounting material containing copper flakes.

One significant feature, which was also seen on most other areas examined, was the level line marking the outer surface of the scale. The line is characterized in varying degrees by several features. First, there is often a dense, pore-free, thin oxide layer lying along this line. Second, there is usually evidence of a crack or physical separation between the dense layer and the underlying scale. Third, there is usually a concentration of a light, sulfur-rich phase lying in the spece between the thin, dense outer scale and the thick, porous inner scale. Where the dense scale layer is thick enough to be discrete and well-defined, the sulfur-rich phase is also found concentrated on the outer surface of this layer as well. Fourth, with rare exceptions, the outer scale layer is level and uniform in thickness, while the thickness of the inner scale may have significant variations.

Figures 66 and 67 are photographs at 775X of two adjacent cusps of depressions in the inner scale. Both are also shown in Figure 65. Figure 66 (negative 23836) shows a shallow cusp. The metal-scale interface is rough but sharp and well-defined. The inner scale is a two-phase mixture of gray Fe_3O_4 matrix and a sprinkling of light sulfur-rick phase. The sulfur phase lies along a fairly straight line and is contiguous with large high-sulfur regions in the deposit. About midway between the deepest part of the cusp and the straight line is a frequently observed feature: a void in close association with a concentration of sulfur-rich phase.

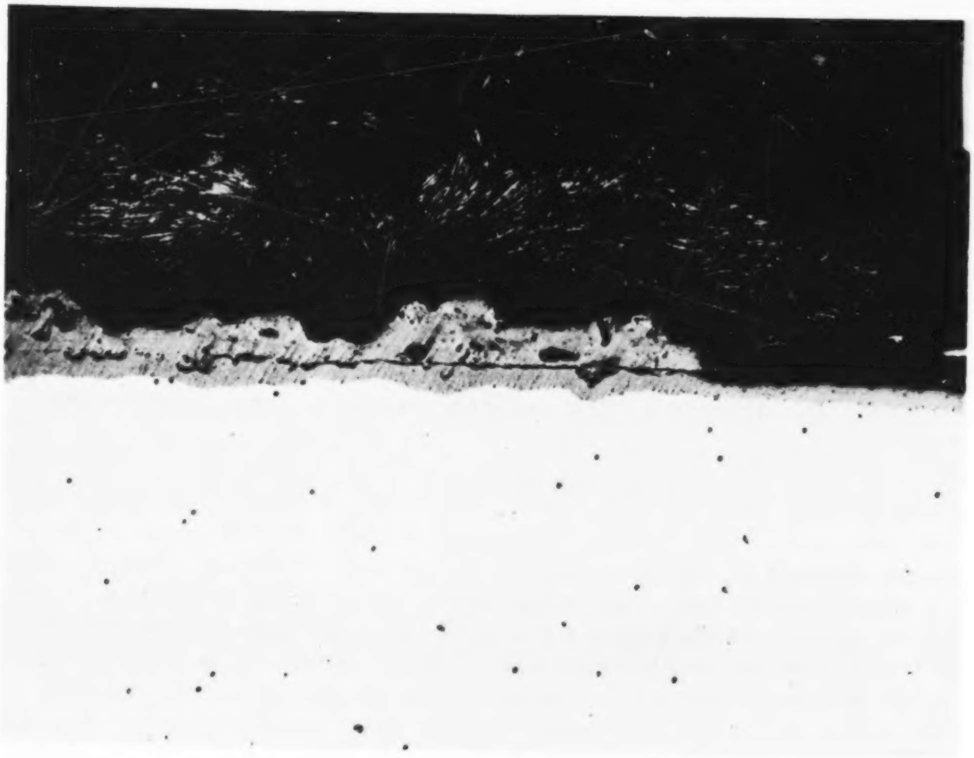

Figure 65. Optical photomicrograph; superheater test specimen, 1,018.5 hr exposure. Cut from fron let of U-tube, finishing superheater. Sharp straight line between scale and heterogeneous deposit. One fairly well developed cusp and one just beginning.

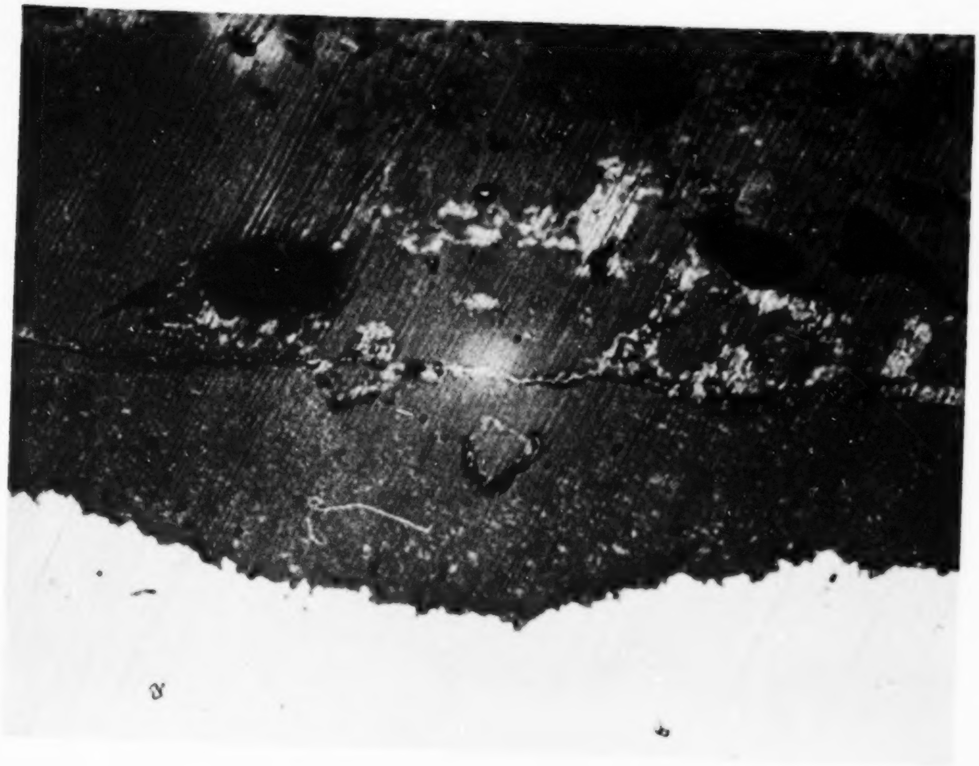

Figure 66. Optical photomicrograph; close-up of newly beginning cusp shown in Figure 65. Midway between the deepest part of the cusp and the straight line is a void in close association with a concentration of sulfur-rich phase.

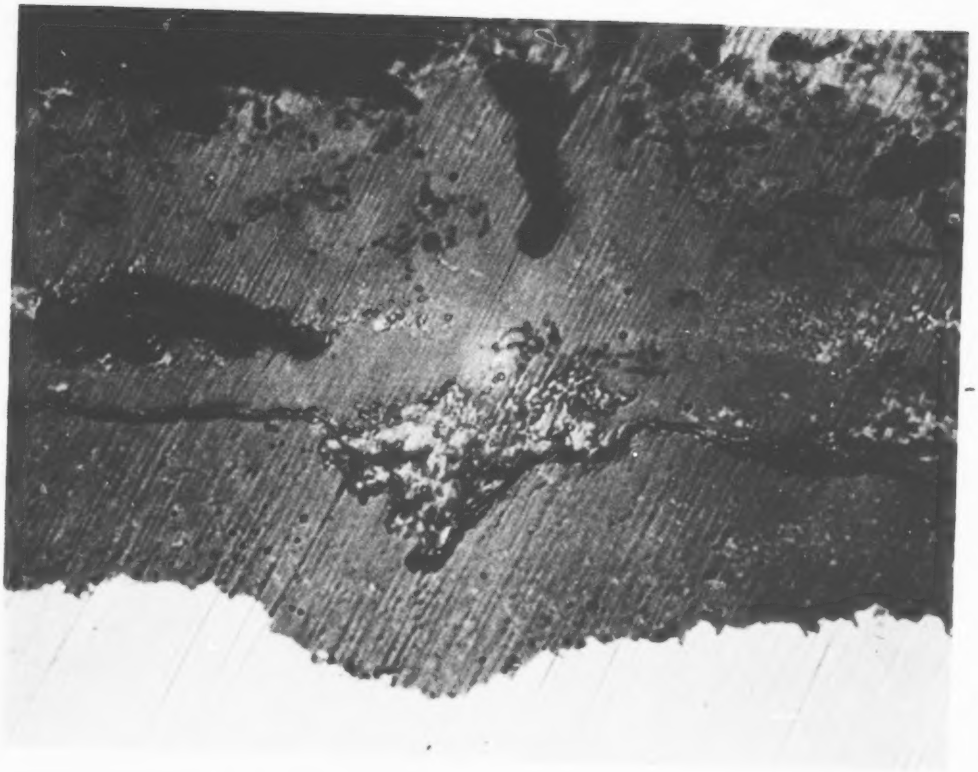

Figure 67. Optical photomicrograph; close-up well-developed cusp shown in Figure 65. Void/sulfur area much larger and intersects straight line between scale and heterogeneous deposit.

Figure 67 (negative 23837) is similar to Figure 66 in that it shows the same sort of metal-scale interface, the porous two-phase inner scale, the line separating scale and deposit, and an association between a void and a concentration of sulfur-rich phase. It differs from Figure 66 in that the void/sulfur area is much larger and intersects the straight line.

Taken together, Figures 65, 66, and 67 are representative of a widely observed set of characteristics which appear to be common to all superheater tube corrosion and which suggest some aspects of a mechanism of scale formation and some facts which must be accounted for by any theory subsequently presented to explain the mechanism.

The straight-line scale interface is almost certainly related to the original metal surface though it doubtlessly lies outward from the original surface. The dense, pore-free scale--not very evident in these pictures, but much clearer in specimens with longer exposure--appears to be the layer of nearly pure oxide which forms initially upon exposure. Upon reaching some critical and fairly uniform thickness, the dense scale appears to be cracked or lifted off the metal surface and a two-phase Fe_3O_4-sulfur phase scale forms between it and the metal. This new scale is noticeably more porous than the initial scale, and in many places it is uniform in thickness and has a uniform dispersion of sulfur. In certain locations, however, the porous scale does pit the metal. Characteristic of these pits are the following: rupture of the dense scale layer or a well-defined crack leading from the metal to the deposit (the latter being less frequently found) and a concentration of light sulfur-rich phase above, at, and below the original scale level, usually in association with voids.

Figure 66 appears to represent an early stage in the formation of a pit, whereas Figure 67 shows a more advanced stage as indicated by the higher sulfur concentration, the more localized and deeply penetrating pit, and the complete disruption of the line marking the original surface.

The question arises whether the pits of cusps were indeed pits caused by corrosive attack or whether they existed prior to exposure to the furnace atmosphere and merely filled in with scale. This question was made more pressing by the discovery of significant pitting in two unused spare superheater tubes. While there have been occasional findings of original surface oxide lying parallel to a curved pit, thus suggesting the prior existence of the pit, the great majority of all pits observed showed clear evidence of the initial formation and subsequent penetration of a smooth, level layer of initial scale.

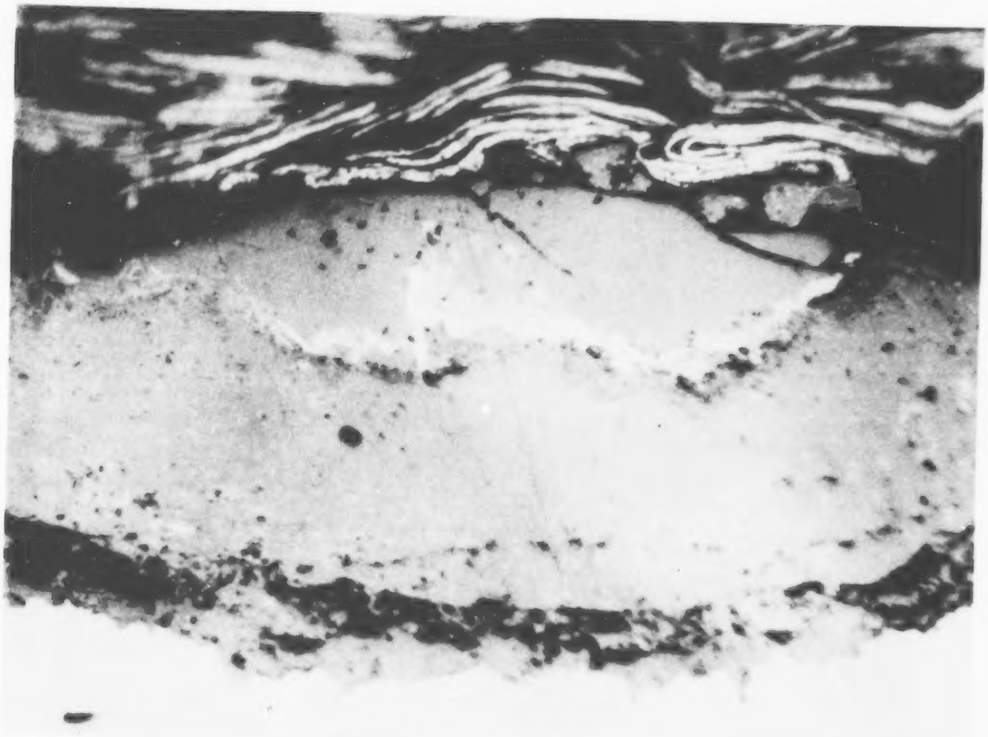

Figure 68. Optical photomicrograph; superheater test specimen, 1,018.5 hr exposure. Cut from return leg of U-tube directly behind specimen shown in Figure 65. Shows a dense scale above and porous scale below a light-colored, sulfur-rich phase.

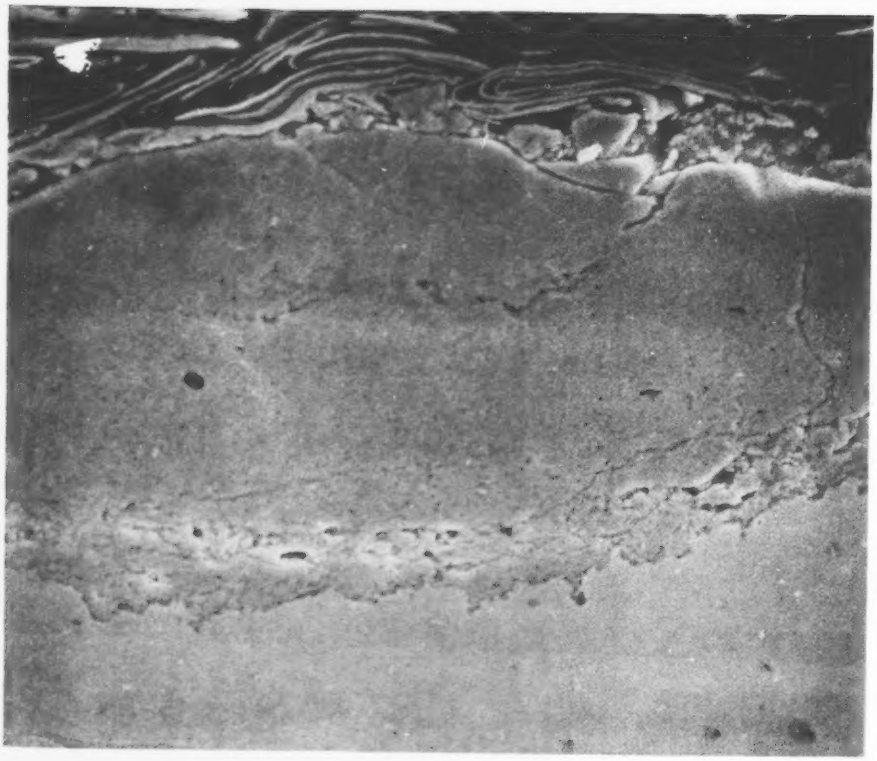

Figure 69. Scanning electron photomicrograph; SEM image of area shown in Figure 68. Fractures and voids near metal/scale interface are not as pronounced as suggested by optical photograph.

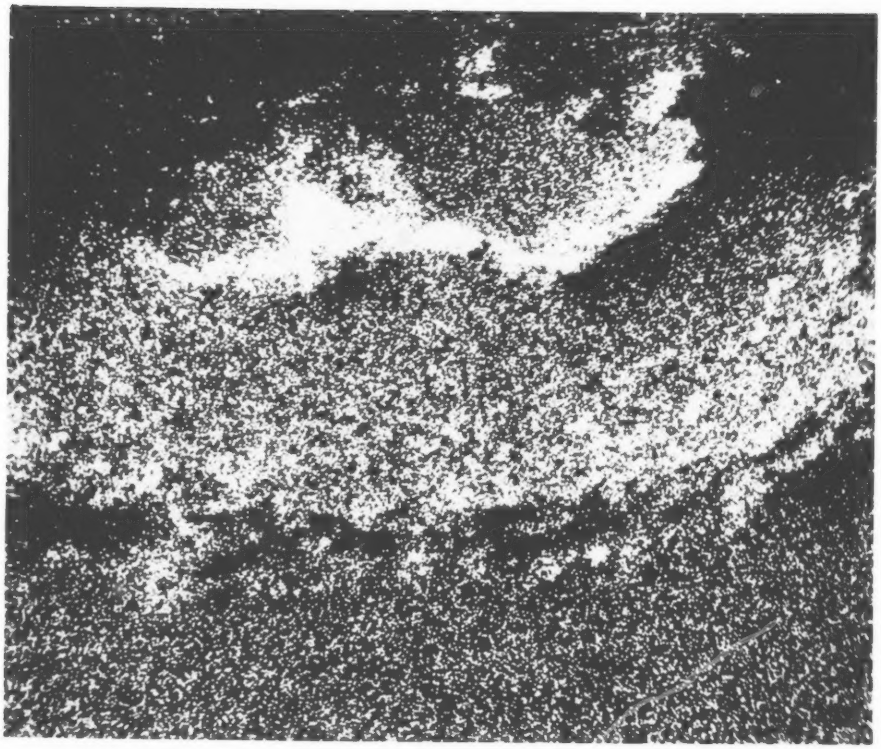

Figure 70. X-ray element distribution image for sulfur in area shown in Figure 68. Shows that sulfur is strongly associated with mottled inner scale and light phase between scales.

These results confirm little sulfur exists in the outer dense scale; it is present in appreciably larger amounts in the inner porous scale; and it is combined in large proportions in the light phase between scales. In the latter case, it is likely that the scanned area on the sample contained some of the gray iron oxide in or slightly below the surface which would tent to increase the Fe/S count ratio. Nevertheless, comparison of the light phase reading with that for known FeS_2 suggests that the light phase is probably some form of iron sulfate or some other compound with a greater Fe/S ratio than exists in FeS_2.

No chemical elements of atomic number greater than 12 were found in any EDAX analysis of the scales. The sensitivity of the instrument is estimated to be 0.1% by weight of the material present. This strongly suggests that the scales are composed almost entirely of iron, oxygen, and sulfur. This in turn suggests that in terms of metal loss or degradation only the two oxidizing elements, sulfur and oxygen, are involved. Sulfur may be carried to the scale surface in some combined form and may exist in deposits in combination with other elements, but the actual corrosion mechanism appears to involve only iron, sulfur, and oxygen.

RESULTS FROM ONE-YEAR EXPOSURE

Test Specimens

Furnace tubes were installed in three waterwall locations and one superheater location on May 19, 1976, and were removed on June 9, 1977. The test sections of the waterwall tubes were each approximately 0.9 m long. When they were removed, approximately 0.9 m of the original tube to which the test specimen was welded was also removed. These sections were then replaced by a single 1.8-m section of new tubing. In the case of superheater tubing, the test specimen consisted of the U-bend section at the bottom of the superheater loop. For comparison purposes, the adjacent original U-bend was also removed. Waterwall tube locations were as follows:

Specimen 34: A section 184 cm long, the lower end of which was 159 cm above the grate. The bottom half of this tube was installed during the original construction. The top half was the test specimen. The tube was on the west wall opposite the fuel injection ports and was the 14th tube from the southwest corner.

Specimen 33: A section 184 cm long, the lower end of which was 52 cm above the grate. The bottom half was the test section, and the top half was original construction. The tube was on the south wall and was the sixth tube from the southwest corner. The test section was as close to the grate as it was possible to place a tube.

Specimen 27: A section 183 cm long, the lower end of which was 157 cm above the grate. The bottom half was the test section, and the top half was original construction. The tube was the center tube on the east wall between and below the fuel distribution.

Superheater specimens were as follows:

Specimen 35: A U-bend section from the front bank of tubes, i.e., the first superheater tubes over which the combustion gases flowed. The tube was the 17th from the south wall. This tube was the test specimen with a 1-year exposure.

Specimen 36: A U-bend section from the front bank of superheater tubes, the 18th from the south wall. This tube had been in place since original construction.

As previously reported, the waterwall tubes were made of a plain low carbon steel conforming to ASTM specification A178, Grade A, or ASTM A192. The superheater alloy was a low carbon 0.5% molybdenum steel conforming to ASTM specification A209.

Waterwall Results

Specimens of the three test sections of waterwall tubing were examined metallographically. In all three cases, there was no discernible corrosion during the 1-year exposure. Many specimens had only a very thin layer of iron oxide scale adhering to the original surface. In some locations, soot and fly ash appeared to be resting directly on the metal surface with no scale evident at optical magnifications. Where any scale was present, it appeared to be either the residue of original mill scale, which is characterized by many cracks, or a thin, pore-free, adherent new scale.

By contrast, the sections of waterwall tubing which had been in place since the original construction of the boiler showed definite evidence of a two-phase, sulfur-containing scale. The degree of attack was slight, but the type of attack was similar to that noted for superheater specimens. There were occasional pits, each associated with a concentration of sulfur-rich phase and immediately adjacent voids or pores. The specimens examined to date do not permit conclusions with respect to the presence or absence of the initial dense oxide layer, but the similarity of the inner scales of superheater tubes and waterwall tubes would suggest that the outer scales would be similar.

It appears, therefore, that over an extended period of time (15-20 years) waterwall tubes can develop scales of the same type observed in the superheater tubes both in short-term and long-term tests but that the rate of reaction at the lower waterwall temperatures is markedly less and is compatible with accpetable performance in boilers using high-sulfur fuel. In the 1-year test with a fuel containing a mixture of RDF and coal, no sulfur-containing scales were found. At present it cannot be stated whether this resulted from the dilution of the coal with RDF or whther the reaction was sufficiently slow that observable amounts of sulfur-containing scale were not generated in 1 year. It can be stated, however, that there is no evidence from the 1-year tests to suggest a deleterious interaction between the combustion products of the coal-RDF mixture and the waterwall tubes.

Superheater Results

The scales resulting from the 1-year exposure of a superheater tube and those found on the original superheater tubes are very similar to one another and to the scales on the 3-month test previously described. The mechanism of scale formation is substantially the same in all three cases.

Figure 71 (negative 23842) is a photograph at 100X of the scale and deposit on the superheater tube exposed for 1 year*. This view is typical of superheater scales. The white material is unetched metal showing polishing scratches. The inner scale is fairly uniform in thickness with no pitting, but it shows both porosity and a dispersion of sulfur-rich phase. The level oxide layer which first formed on the metal surface is not very distinct in this picture but appears to lie just above the heavy sulfur-rich layer. Above the sulfur layer is the heterogeneous deposit.

Figure 72 (negative 23841) is a photograph at 775X of a part of the same area shown in Figure 71. In this figure, the single-phase nature of the high-sulfur area is evident. (Below this layer is the two-phase inner scale; above it may be the remnants of the original oxide scale; and beyond is the deposit which contains significant high-sulfur regions.) X-ray element distribution images and EDAX analysis showed that iron was distributed quite uniformly over the area shown in Figure 72, sulfur was concentrated at the

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* When specimens are made, a ring is cut from the tube. In turn, this is sectioned such that the half circle from the front (facing the gas stream) to the rear is subdivided into four parts, each comprising a 45 degree arc of the original tube. Figure 71 shows the scale at one of the cuts between segments of tube; the copper-containing mounting material is visible at the side of the specimen.

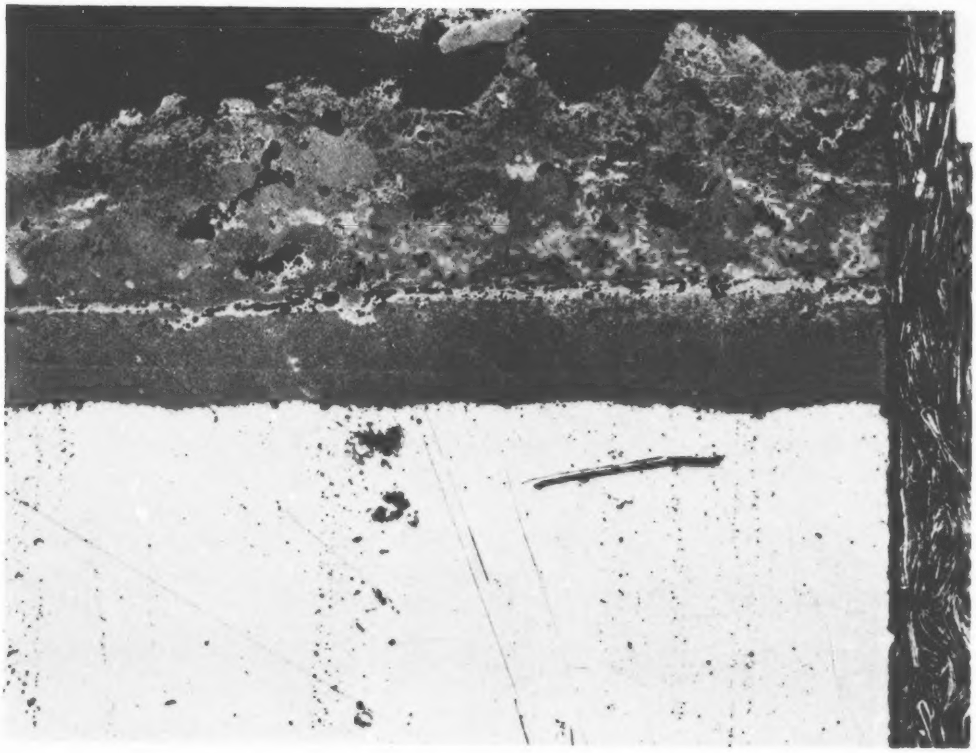

Figure 71. Optical photomicrograph; superheater test specimen, 1-year exposure. Uniform thickness inner scale, porous with a dispersion of sulfur-rich phase. Thin layer of sulfur-rich phase between porous scale and heterogeneous deposit.

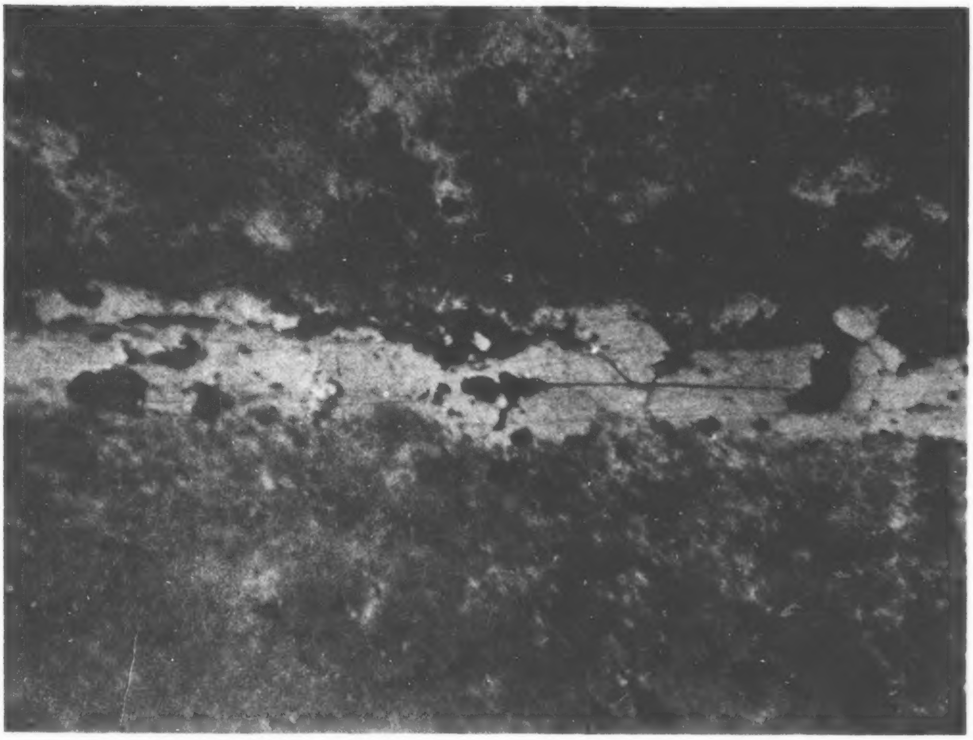

Figure 72. Optical photomicrograph; close-up of area near the right side of specimen shown in Figure 71, showing sulfur-rich phase between porous scale and heterogeneous deposit.

light areas, and no other elements with an atomic number greater than 11 (Na) were present in more than minute trace amounts.

These results suggest an exact duplication of mechanism in the corrosive attack in the 3-month and 1-year specimens. Comparison of Figures 65 and 71 show that the longer term exposure produced a thicker scale, but in both instances the original metal surface is still reflected by the scale/deposit interface. The degree of atack and thickness of scale do vary from the front to the back of the superheater tube; it is less at the rear. Figures 65 and 103 show areas at the front face of the tube and thus are representative of the most severe attack observed. The scale formed in 1,000 hr is approximately 0.025 mm (0.001 in.) thick, and that formed in 1 year is approximately 0.127 mm (0.005 in.) thick. As noted below, the scale observed on the superheater tube in service from the data of original construction is about 0.102 mm (0.004 in.) thick, which shows that the scale thickness tends to stabilize at about that value.

Two areas observed on the original superheater tube provide some further insight into the mechanism of corrosive attack. Figure 73 (negative 23843) is a photograph at 100X of the scale on the front surface of the U-section. The texture of the scale is less sharply defined than in other specimens, but the separation between scale and deposit can still be seen along with the typical pores and distributed sulfur-rich phase. Some pitting is noted, but the original oxide layer is absent or degenerated beyond recognition. The surface shown in this view was subjected to soot blowing and high radiant heat during its entire lifetime.

Figure 74 (negative 23839) shows a section at 100X of the scale on the rear leg of the same original U-shaped superheater tube shown in Figure 73. The surface shown was also facing the flow of hot gas but was protected by the other leg of the U in front of it. Here, a much more sharply defined scale structure can be seen. The original level layer of outer oxide is clearly visible along with three well-developed pits. The metal loss due to oxidation has been almost nil except in the presence of the pits. All the features which are apparently characteristic of this mode of attack can be observed in this general area: pits, porous inner scale; dense outer scale, sulfur-containing phase dispersed in the inner scale and present as layers along the outer scale and as irregular accumulations in the deposit, and cracking at the inner/outer scale interface.

An enlarged view of one of the three pits is shown in Figure 75, taken at 775X. This shows yet another feature of the pitting attack. Pits always appear to occur at a breach or defect in the original outer scale, and there is always a void and a concentration of sulfur at the center of the pit. The clear "tree-ring" effect noted here suggests that pit growth is not a continuous, steady process but may be associated with variations in the conditions of exposure.

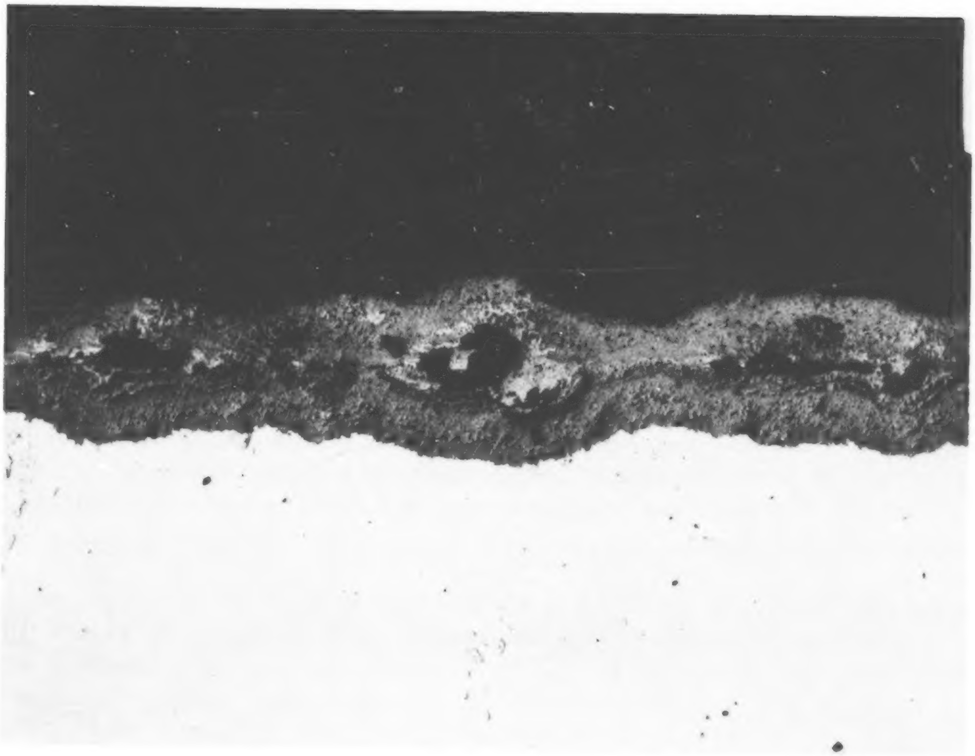

Figure 73. Optical photomicrograph; superheater test specimen, original construction. Cut from front leg of U-tube, finishing superheater. Distinct separation between porous inner scale and heterogeneous deposit.

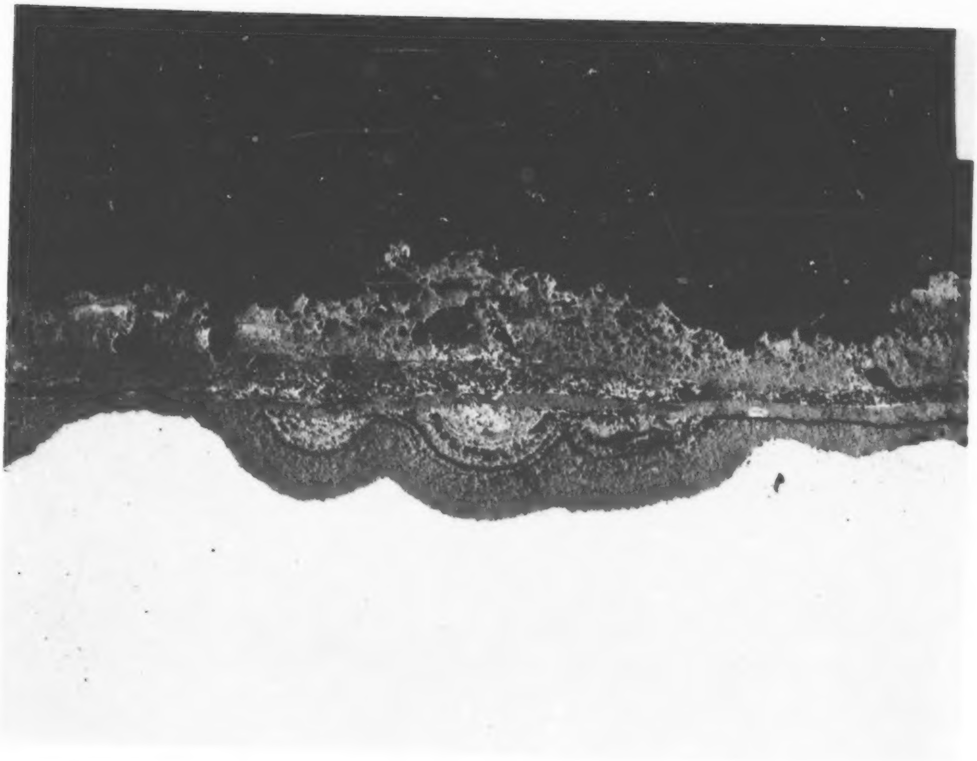

Figure 74. Optical photomicrograph; superheater test specimen, original construction. Cut from return leg of U-tube directly behind specimen shown in Figure 73. Sharply defined scale layers. Well-developed pits associated with concentration of sulfur-rich phase and void areas.

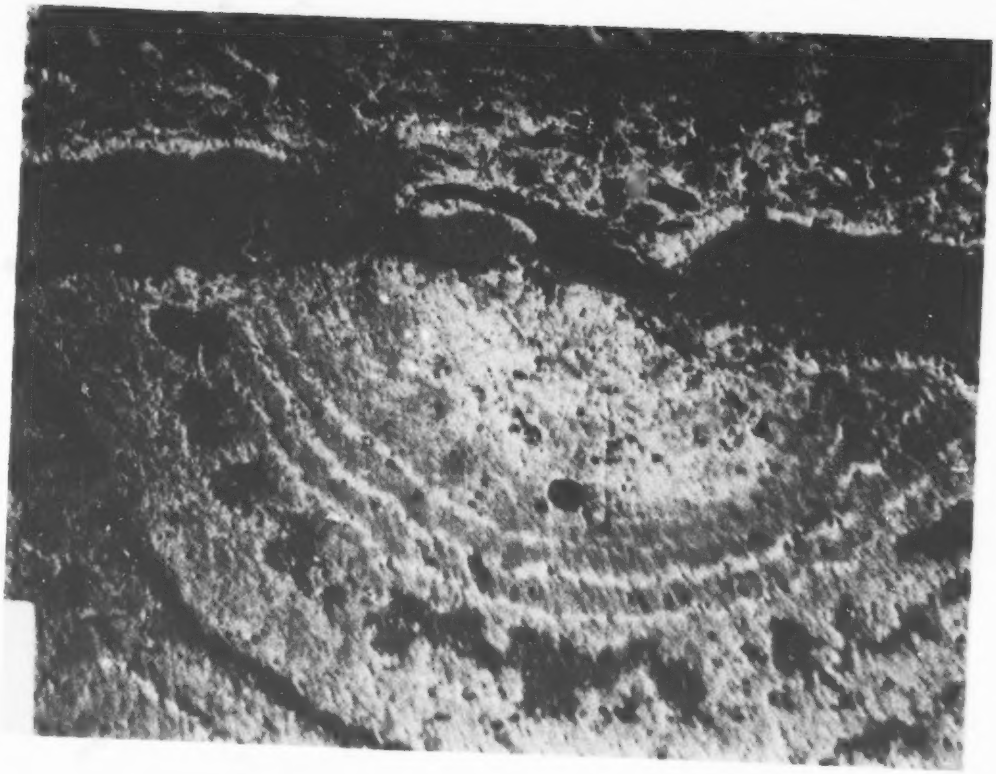

Figure 75. Optical photomicrograph; close-up of scale layers and sulfur concentration shown in the center of Figure 74. Shows a fault in dense oxide scale with sulfur concentration directly beneath.

On rare occasions a defect can be found such as is shown in Figure 76 (negative 23844), a photograph at 100X of the superheater tube exposed for 1 year. The defect is a crack running perpendicularly from the base of a pit to the outer scale layer. Such cracks are usually filled with a light-colored sulfur phase. In this figure can also be seen the well-defined outer oxide, sulfur, and voids accumulated below the original surface, and the suggestions of a layer-like growth pattern in the inner scale.

DISCUSSION

Superheater Tubes

The scales on all superheater tubes have been found to exhibit the same structure, irrespective of period of exposure. This implies that a single mechanism of oxidation exists in all cases observed. The addition of RDF to the fuel has not altered the mechanism of attack, and there is no evidence to suggest any alteration of the rate of attack. The scale thickness appears to reach a stable value of the order of 0.127 mm. In most cases, it was possible to observe the scale initially formed on the metal surface, thus giving a benchmark from which to measure scale thickness.

The observed scale appears to be basically composed of a thin outer layer, probably Fe_2O_3, and a thicker inner layer, probably Fe_3O_4. Sulfur is distributed in this scale, probably in a combined form as a sulfate, in a complex fashion. It exists as a single-phase layer in radial cracks, in lateral cracks at the interface between the two oxide scales, and on top of the thin outer scale. It is also present irregularly in the superimposed deposit. Concentrations of sulfur are uniquely associated with defects in the outer scale layer and with hemispherical enlargements of the scale below the defects which result in pits in the metal.

Although pits are found in all superheater specimens and although it is clear that these pits result in a local increase in the depth of penetration, none of these pits appears to extend to a depth more than about two or three times the depth of the uniform scale, and none appears to have experienced catastrophic growth. Uniform scale layers are of the order of 0.127 mm thick, and maximum penetrations are of the order of 0.254 to 0.381 mm. Thus, sulfur does appear to make matters worse, but not sufficiently worse to be of practical concern under the conditions experienced by boiler Unit 5 during its lifetime.

The exact mechanism of the oxidation of superheater tubes had not yet been determined. Attempts will continue to be made to identify the phases present by x-ray diffraction studies of bulk mixed scales or by x-ray diffraction analysis of particles removed from selected areas of scales. It is anticipated that when positive phase identification has been made, a suitable thermodynamic and kinetic interpretation can be offered based upon prior research in the Fe-S-O system.

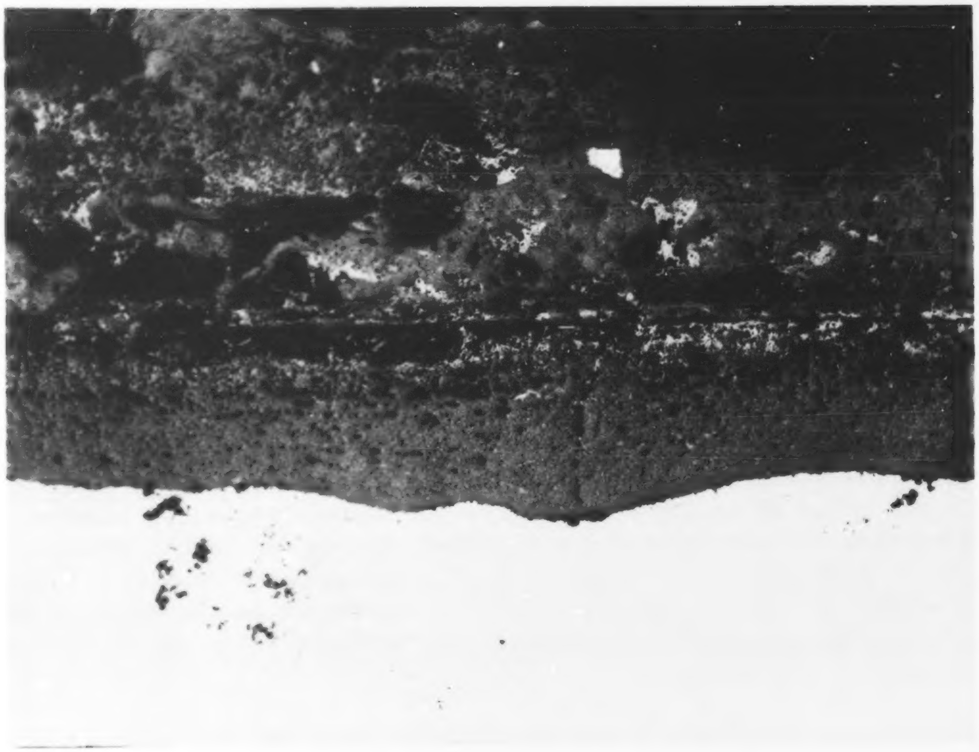

Figure 76. Optical photomicrograph; superheater test specimen, 1-year exposure. Porous inner scale with crack running perpendicular to well-defined pit in metal.

Certain practical conclusions can be drawn, however, even in the absence of complete analytical data and thermodynamic interpretation. First, the addition of RDF did not alter the mechanism, which has been found to be tolerable under conditions of firing with 100% coal. Second, localized attack appears to be associated with concentrations of sulfur. To the degree that sulfur levels in the combustion atmosphere are reduced by the dilution effect of RDF, the addition of RDF should be expected to reduce rates of scaling. Third, the scale in contact with the metal, which is the active agent in any corrosive mechanism, appears to be composed entirely of iron, oxygen, and sulfur and to be substantially unrelated to the composition of the heterogeneous superimposed deposit. Thus, it appears that the complex chemistry of the deposit can be eliminated as a direct factor in the oxidation mechanism though it may in some way influence the kinetics of the reaction; i.e., ultimate understanding of the mechanism and kinetics of the Fe-O-S reaction may suffice for an adequate understanding of the overall oxidation reaction notwithstanding the much more complex composition of the deposit and the combustion atmosphere.

Waterwall Tubes

Waterwall tubes from three locations in the boiler have been examined after exposure times of 1,000 hr and 1 year. These results have been compared with observations made on waterwall tubes installed during original construction.

Tubes exposed up to 1 year have very thin scales which appear to be composed only of iron oxide in a dense, adherent layer. There was no microscopic evidence of sulfur compounds in the scales, nor was there any evidence of pitting. All scales were very thin, and metal attack was nil.

Waterwall tube specimen 33 consisted of a test section which extended from about 1.5 to 2.4 m above the grate. The original construction tube occupied the space between about 1.2 and 1.5 m above the grate. A specimen taken from this piece of original construction waterwall tube had a scale structure similar to that observed in the superheater tubes. This is the only waterwall specimen found with such a scale. The inner scale next to the metal was porous and contained a finely dispersed, light-colored second phase. A pit was found which contained a concentration of the light phase and an associated void at the center of the pit. EDAX analysis revealed concentrations of sulfur in areas where light phase appeared.

It appears, therefore, that under the combustion conditions nearest the grate, waterwall tubes can produce the same type of oxidation noted in superheater tubes, whereas conditions near other waterwall tubes do not. Nevertheless, the metal penetration was very slight (0.05 mm) and was a consequence of earlier operations using only coal as the fuel. Thus, this type and rate of attack are not associated with the burning of RDF and are well within acceptable operational limits.

SUMMARY

The burning of RDF mixed with coal does not alter the basic mechanism of corrosion found to exist on superheater and waterwall tubes when coal is burned alone. There is no evidence to suggest that the presence of RDF causes an acceleration of the rate of attack. Pitting is observed on all superheater tubes and old original-construction waterwall tubes. These pits are associated with sulfur. It is possible, but not yet proven, that the presence of sulfur is a causative agent in the formation of pits. However, it has been shown through operating experience as well as direct measurement of pit depth that this type and degree of oxidation damage are within acceptable operating limits. The presence of deposits of complex chemical composition does not alter the basic oxidation mechanism or the composition of scales, which appear to be composed almost entirely of iron, oxygen, and sulfur. Deposits may affect the kinetics of the oxidation reaction, but no tests of this effect have been made.

REFERENCES

1. Even, J. C., S. K. Adams, P. Gheresus, A. W. Joensen, and J. L. Hall. Evaluation of the Ames Solid Waste Recovery System, Part I: Summary of Environmental Emissions: Equipment, Facilities, and Economic Evaluations, EPA-600/2-77-205, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

2. Gheresus, P. The Ames Solid Waste Resource Recovery System: Operation Cost, and Revenue Analysis. M. E. Technical Report, Department of Industrial Engineering, Iowa State University, Ames, Iowa, 1977.

3. Kosolcharoen, C. The Ames Solid Waste Conveying and Storing System: Operation and Cost Analysis. M. E. Technical Report, Department of Industrial Engineering, Iowa State University, Ames, Iowa, 1977.

4. Hinderaker, P. (City of Ames, Iowa), city records and personal communication.

5. Hall, J. L., A. W. Joensen, D. Van Meter, R. Wehage, G. Severns, R. Reese, H. R. Shanks, D. E. Fiscus, and R. W. White. Evaluation of Ames Solid Waste Recovery System, Part III: Environmental Evaluation of the Stoker-Fired Steam Generators, EPA-600/7-79-222, U.S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

6. Hall, J. L., G. Severns, A. W. Joensen, H. Shanks, and R. White. Environmental Emissions of Stoker-Fired Boilers. Year II Special Report, in review, 1978.

7. Van Meter, D., A. W. Joensen, W. L. Larsen, R. Reese, J. L. Hall, D. E. Fiscus, and R. W. White. Evaluation of the Ames Solid Waste Recovery System, Part II: Evaluation of the Stoker-Fired Steam, EPA-600/7-79-229, U.S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

8. Standards of Performance for New Stationary Sources. Federal Register, Vol. 36, No. 247, Pt. 11, December 23, 1971.

9. Standards of Performance for New Stationary Sources. Amendments to Reference Methods. Federal Register, Vol. 41, No. 111, Pt. 11, June 8, 1976.

10. Standards of Performance for New Stationary Sources. Federal Register, Vol. 38, No. 66, Pt. 11, April 6, 1973.

11. Fassel, V. A. and R. N. Knissley. Inductively Coupled Plasma-Optical Emission Spectroscopy. Analy. Chem., 46:110A, 1974.

12. Carottu, A. A. and E. R. Kaiser. Concentrations of Twenty Gaseous Chemical Species in the Flue Gas of a Municipal Incinerator. JAPCA, 22:249, 1972.

13. Even, J. C. Economic Evaluation, Part I: Evaluation of the Ames Solid Waste Recovery System. U.S. Environmental Protection Agency, August 1977.

14. Olexsey, R. A., C. C. Wiles, C. L. Kulwicki, A. W. Joensen, and J. L. Hall. Operation of the Stoker Boilers Firing Coal and Refuse at Ames, Iowa. Fifth National Conference on Energy and the Environment. Paper No. 2.6. Cincinnati, Ohio, October 31-November 3, 1977.

15. Wiles, C. C., D. E. Fiscus, R. A. Olexsey, A. W. Joensen, and J. L. Hall. Derived Fuel Recovery System. Fifth National Conference on Energy and the Environment. Paper No. 8.1, Cincinnati, Ohio, October 30-November 3, 1977.

16. Shanks, H. R., J. L. Hall, and A. W. Joensen. Environmental Effects on Burning Solid Waste as Fuel. Fourth Joint Conference on Sensing of Environmental Pollutants. Paper No. 195, New Orleans, Louisiana, November 6-11, 1977.

17. Hall, J. L., H. R. Shanks, A. W. Joensen, D. B. Van Meter, and G. A. Severns. Emission Characteristics of Burning Refuse-Derived Fuel with Coal in Stoker-Fired Boilers. Air Pollution Control Association Annual Meeting and Exhibition. Paper No. 78-18.3, Houston, Texas. June 25-30, 1978.

18. Hall, J. L., G. A. Severns, A. W. Joensen, D. B. Van Meter, and H. R. Shanks. Operation and Emissions of Stoker-Fired Boiler while Burning Refuse Derived Fuel and Coal Mixtures. American Socity of Mechanical Engineers Winter Annual Meeting. San Francisco, California, December 10-15, 1978.

19. Armar, J. N. and J. A. Burke. Method of Separating Polychlorinated Biphenols from DDT and Its Analogs. JAOAC, 53:761, 1970.

20. Gladney, E. S., J. A. Small, G. E. Gordon, and W. A. Zoler. Composition and Size Distribution of In-Stack Particulate Material at a Coal-Fired Power Plant. Atmospheric Environment, 10:1071-1077, 1976.